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SUBSURFACE ANALYSIS OF THE MESAVERDE GROUP ON AND NEAR THE JICARILLA APACHE INDIAN RESERVATION, NEW MEXICO—ITS IMPLICATION ON SITES OF OIL AND GAS ACCUMULATION

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By:
Jennie Ridgley

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Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

Virginia Weyland, Project Manager
National Petroleum Technology Office
P.O. Box 3628
Tulsa, OK 74101

Prepared by
U.S. Geological Survey
MS 939 Box 25046DFC
Denver, CO 80225

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ABSTRACT

A goal of the Mesaverde project was to better define the depositional system of the Mesaverde Group in hopes that it would provide insight to new or by-passed targets for oil exploration. The new, detailed studies of the Mesaverde give us a better understanding of the lateral variability in depositional environments and facies. Recognition of this lateral variability and establishment of the criteria for separating deltaic, strandplain-barrier, and estuarine deposits from each other permit development of better hydrocarbon exploration models, because the sandstone geometry differs in each depositional system. Although these insights will provide better exploration models for gas exploration, it does not appear that they will be instrumental in finding more oil.

Oil in the Mesaverde Group is produced from isolated fields on the Chaco slope in the southwest part of the San Juan Basin; only a few wells define each field. Production is from sandstone beds in the upper part of the Point Lookout Sandstone or from individual fluvial channel sandstones in the Menefee Formation. Stratigraphic traps rather than structural traps are more important. Source of the oil in the Menefee and Point Lookout may be from interbedded organic-rich mudstones or coals rather than from the Lewis Shale. The Lewis Shale appears to contain more type III organic matter and, hence, should produce mainly gas. Outcrop studies have not documented oil staining that might point to past oil migration through the sandstones of the Mesaverde. The lack of oil production may be related to the following: 1) lack of abundant organic matter of the type I or II variety in the Lewis Shale needed to produce oil, 2) ineffective migration pathways due to discontinuities in sandstone reservoir geometries, 3) cementation or early formation of gas prior to oil generation that reduced effective permeabilities and served as barriers to updip migration of oil, or 4) erosion of oil-bearing reservoirs from the southern part of the basin. Any new production should mimic that of the past, i.e. be confined to small fields in isolated sandstone beds.

INTRODUCTION

The purpose of the phase 2 Mesaverde study part of the Department of Energy funded project "Analysis of oil- bearing Cretaceous Sandstone Hydrocarbon Reservoirs, exclusive of the Dakota Sandstone, on the Jicarilla Apache Indian Reservation, New Mexico" was to define the facies of the oil-producing units within the subsurface units of the Mesaverde Group and integrate these results with outcrop studies that defined the depositional environments of these facies within a sequence stratigraphic context. As currently defined, there are two principal intervals of oil production within the Mesaverde Group. The bulk of the oil production comes from sandy, fluvial channel facies in the Menefee Formation and the remaining from shoreface sandstone facies of the Point Lookout Sandstone. The focus of this report will center on 1) integration of subsurface correlations with outcrop correlations of components of the Mesaverde, 2) application of the sequence stratigraphic model determined in the phase one study to these correlations, 3) determination of the facies distribution of the Mesaverde Group and their relationship to sites of oil and gas accumulation, 4) evaluation of the thermal maturity and potential source rocks for oil and gas in the Mesaverde Group, and 5) evaluation of the structural features on the Reservation as they may control sites of oil accumulation. Discussion of the above is found in the text below and in a series of five cross sections (plates 1-5), one structure map (plate 6), and four tables.

REGIONAL GEOLOGY

The Jicarilla Apache Indian Reservation is located on the northeast side of the San Juan Basin in northwestern New Mexico (fig. 1). The Reservation boundary is irregular and because of this both geologic formations and structural elements cross the Reservation at odd angles. As a result of the orientation of both the geology and structural features with respect to the Reservation boundary, certain facies are not always present within the Reservation confines, although they may be present in areas adjacent to the Reservation. Similarly, structural features may lie wholly or partially within the Reservation or be totally absent, although they occur in adjacent areas. Outcrops of Cretaceous rocks that are the focus of this investigation are confined to the northeast side of the Reservation.

STRATIGRAPHY

Upper Cretaceous rocks that crop out on and near the Reservation in ascending order include: Dakota Sandstone, Mancos Shale, Dalton Sandstone Member of the Crevasse Canyon Formation, Mesaverde Group, Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, and Kirtland Shale. The stratal relationships of those formations addressed in this report are summarized in figure 2. Summaries of the Cretaceous formations can be found in (Fassett, 1974; Landis and Dane, 1967; Landis and others; 1974; Molenaar, 1974; 1977). Only rock comprising the Mesaverde Group will be treated more fully below.

Mesaverde Group

The Mesaverde Group consists of, in ascending order, the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone Their relationships to the overall San Juan Basin stratigraphy are shown in figure 3. The Point Lookout Sandstone was deposited in nearshore marine environments; the basal part is interbedded with the Mancos Shale. The Menefee Formation reflects deposition in fluvial and estuarine environments. The Cliff House Sandstone was deposited as marine sandstone. The Mesaverde Group is found throughout the San Juan Basin; it is thickest in the southern part of the basin where it exceeds 2000 ft (610 m) (fig. 3). The three units that comprise the Mesaverde vary in thickness throughout the basin. The change in thickness, in part, reflects the northeast stratigraphic rise of the Mesaverde during progradation to

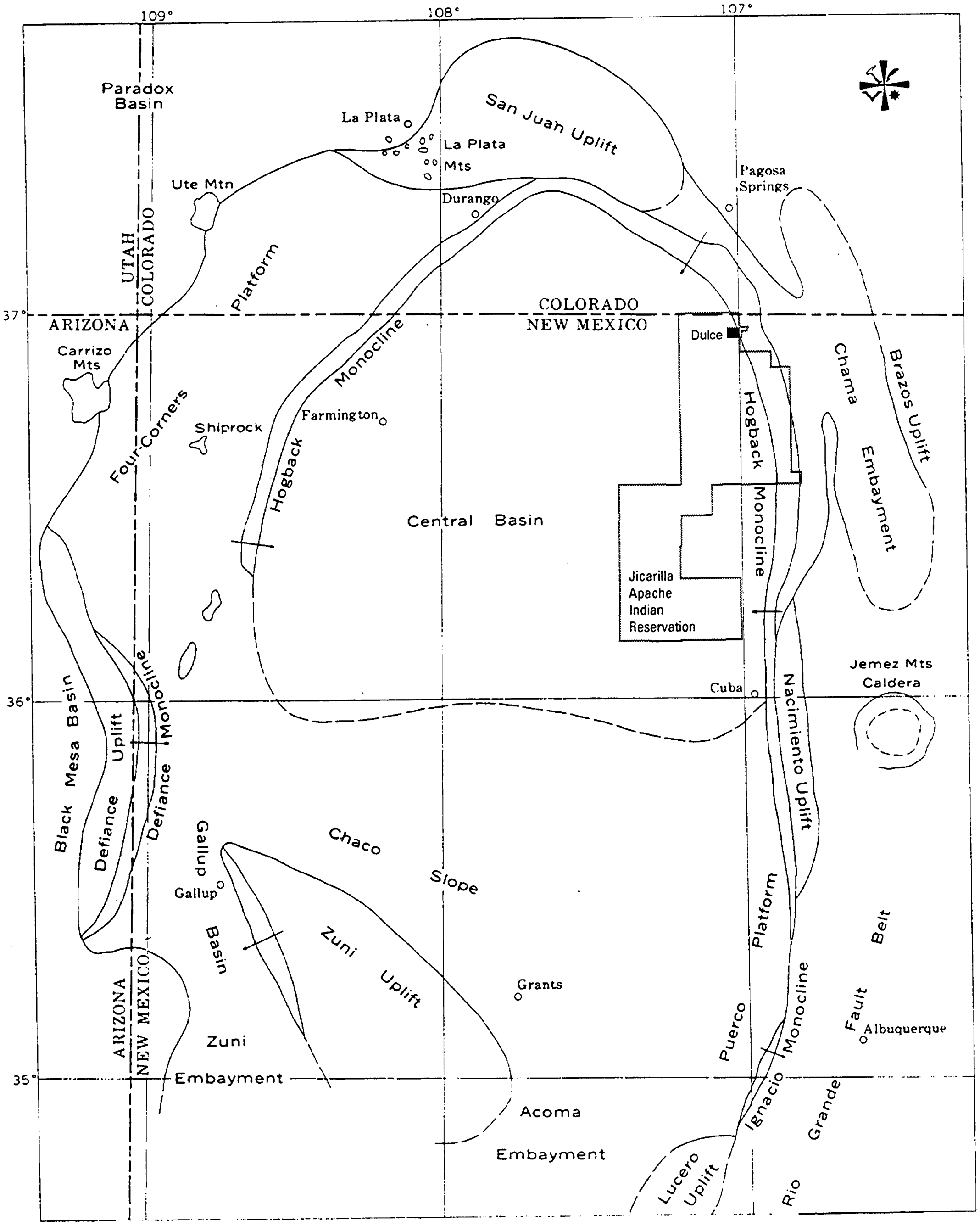


Figure 1. Map of the San Juan Basin showing principal structural elements and location of the Jicarilla Apache Indian Reservation.

the northeast. Thickness of the Mesaverde also appears to have been controlled by subtle movement on basement-controlled structural blocks. Studies of seismic reflection data suggest the presence of basement-controlled structural blocks (Taylor and Huffman, Jr, 1998; Taylor and Huffman, Jr, 2000), some of which appear to have been active during deposition of the Mesaverde. Each of the formations that comprise the Mesaverde is summarized below. More complete discussion of the depositional sequences can be found in Fassett (1977), Fuchs-Parker (1977), Molenaar (1977), Katzman and Wright Dunbar (1992), Wright Dunbar and others (1992), and Wright-Dunbar (2000a).

Point Lookout Sandstone

Throughout the southern two-thirds of the basin, the Mesaverde consists of stacked parasequences that reflect deposition during progradation. These parasequences consist of an upward succession of shale, interbedded sandstone and shale, and sandstone. The basal shale beds (Mancos Shale) represent deposition in deeper marine environments and can be regarded as the fourth-order flooding surfaces. The mixed sandstone and marine shale were deposited in offshore transition environments and represents the interbedding of distal toes of shoreface sandstone of the Point Lookout Sandstone with marine mudstone of the Mancos Shale. The sandstone facies of the Point Lookout reflect deposition in coastal marine environments primarily as shoreface deposits, although elsewhere in the basin deltaic deposits have been described (Wright Dunbar and others, 1992). Thickness of the Point Lookout ranges from 150 ft (45.7 m) to about 200 ft (61 m) (plates 1-5) in the subsurface to as much as 230 ft (70.1 m) at the outcrop (Wright Dunbar, 2000a). The variation in thickness observed in wireline logs and outcrop measured sections in part reflects how much of the interbedded transition facies and underlying shale facies were included in the Point Lookout. Otherwise the principal reason for variation in thickness is related to periods of aggradation during still-stands versus times when simple progradation was dominant. The Point Lookout is thickest during the periods of aggradation. The stratigraphic rise of the Point Lookout from the southwest to the northeast part of the San Juan Basin is about 1200 ft (366 m) (Molenaar, 1977). Overall, the Point Lookout thins to the northeast, and in the Colorado part of the San Juan Basin west of Pagosa Springs, the Point Lookout merges with the Cliff House Sandstone.

Menefee Formation

The Menefee Formation reflects deposition in nomarine environments landward of the marine Point Lookout Sandstone and Cliff House Sandstone. It is composed of vertically stacked channel sandstone deposited in fluvial environments. The channel sandstones are interbedded with nonmarine overbank shales, which are locally carbonaceous, paludal carbonaceous shales, and coals. The coal beds are laterally discontinuous and are commonly less than a few feet thick. The Menefee is thickest in the southwest part of the San Juan Basin where it is about 2000 ft (610 m) thick (Molenaar, 1977). It thins to the northeast where it pinches out between the Lewis Shale and the Point Lookout Sandstone (figs. 3 and 4; plates 1-5).

Cliff House Sandstone

The Cliff House Sandstone was deposited during brief regressions or still-stands as nearshore coastal standplain sandstone during an overall sea level rise associated with transgression. The sandstone beds of the Cliff House intertongue with the Lewis Shale in a seaward direction to the northeast and with the Menefee Formation in a paleo-landward direction to the southwest (plates 1-5). The Cliff House Sandstone forms a series of amalgamated sandstone benches that step up stratigraphically to the southwest (fig. 3; Molenaar, 1977; Fassett, 1977). The benches are thickest at points of stratigraphic rise associated with periods of aggradation during still-stands. In between the thick sandstone benches, sandstone of the Cliff

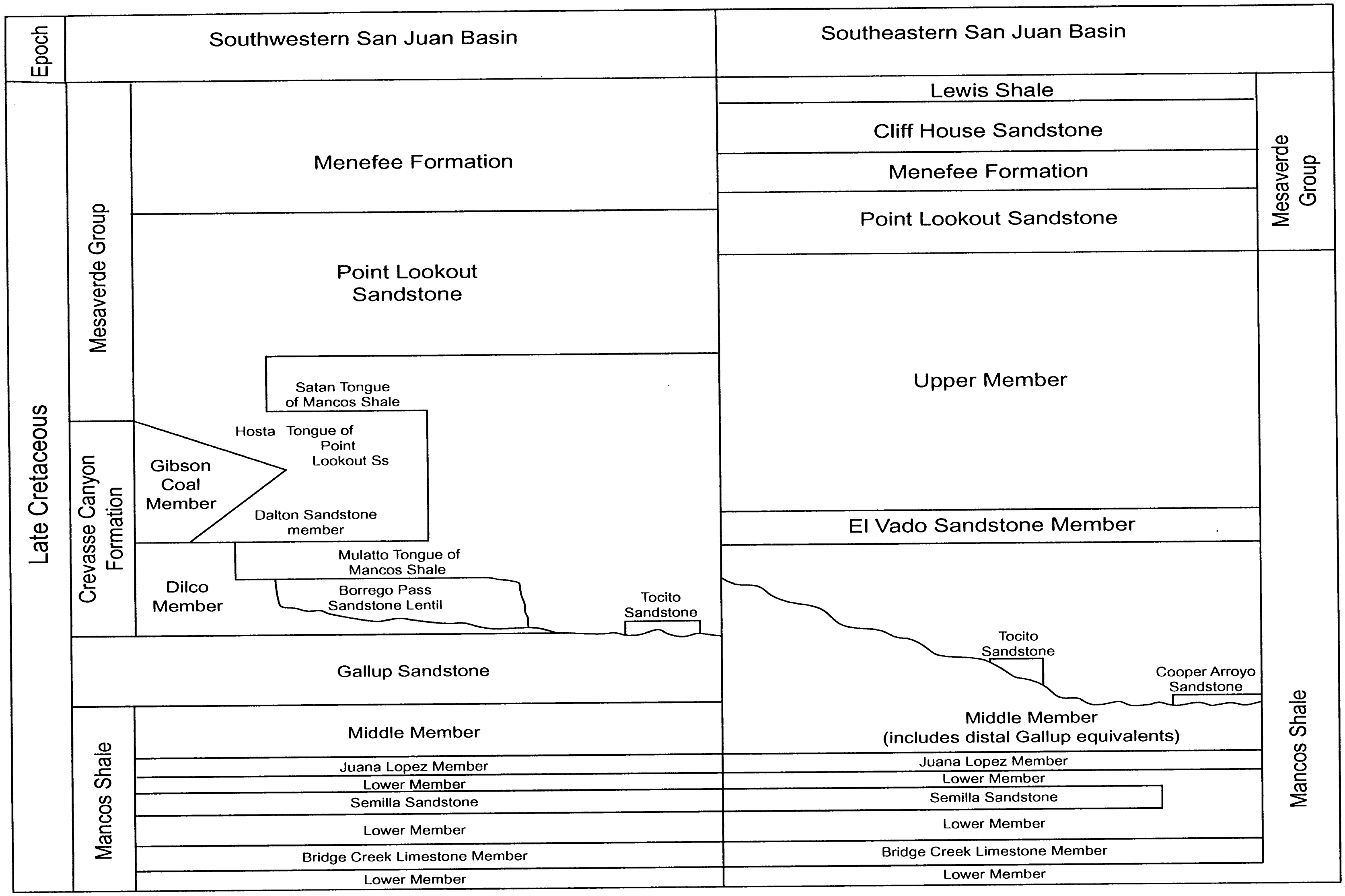


Figure 2. Chart showing correlation of selected Cretaceous formations in the southwestern and northeastern part of the San Juan Basin.

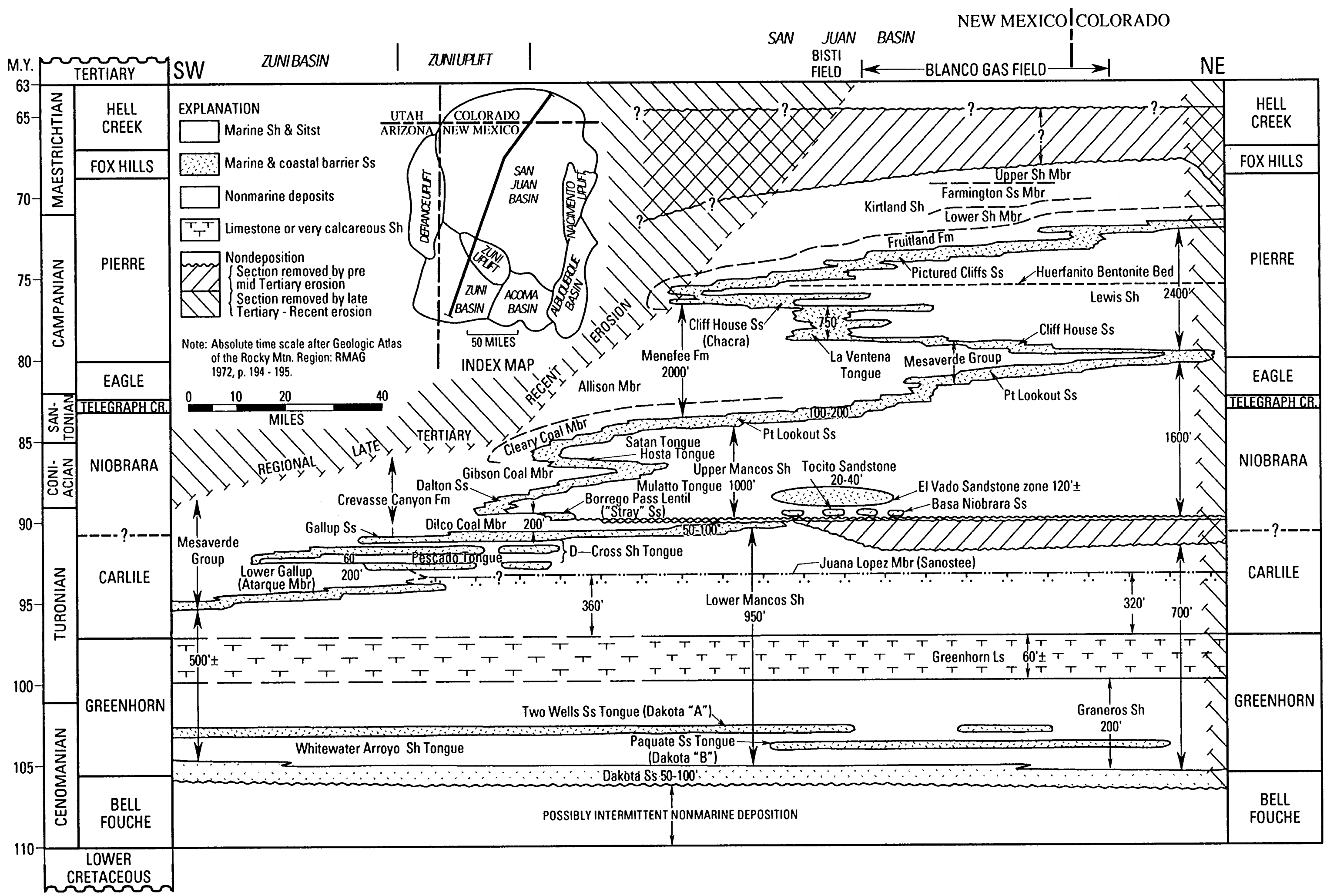


Figure 3. Time - stratigraphic cross section of Upper Cretaceous and Tertiary rocks in the San Juan Basin. Modified from Pentilla (1964) and Molenaar, 1974).

House is much thinner. The thinner sandstone represents deposition during a landward shift in the shoreline to the southwest. In the study area, the Cliff House ranges from 0 ft in the northeast to as much as 150 ft (45.7 m) in the central part of the study area (plates 1-5). The basal deposits accumulated in nearshore environments and grade laterally into the nonmarine Menefee Formation. Upwards, the sandstone deposits of the Cliff House are entirely marine and represent deeper water lower shoreface and inner shelf environments (Nummedal and others, 1989). The sandstone referred to as the Cliff House Sandstone on cross sections (plates 1-5) is the basal Cliff House Sandstone of Fassett (1977).

The thickest buildup of the Cliff House Sandstone, referred to as the La Ventana Tongue, occurs to the west and south of the study area where it ranges in thickness from 600 to 800 ft, respectively (Fassett, 1977; Molenaar, 1977). The La Ventana Tongue interfingers with the Menefee Formation to the southwest and with the Lewis Shale to the northeast. The Lewis Shale separates the La Ventana Tongue from an overlying smaller buildup of sandstone, also assigned to the Cliff House. This upper sandstone buildup is called the Tsaya Canyon sandstone member of the Cliff House Sandstone (Fassett, 1977). The Tsaya Canyon sandstone is not shown on the 5 regional cross sections. There is no oil produced from this member nor from the La Ventana Tongue or basal Cliff House sandstones. Thin sandstone beds (not shown on the cross sections) in the Lewis Shale that occur stratigraphically below the Huerfanito bentonite bed in the deeper part of the basin are considered to be offshore-bar equivalents to the upper part of the La Ventana Tongue (Molenaar, 1977). These sandstones are the "Chacra" sandstones of drillers and they produce gas in the deeper part of the San Juan Basin.

Lewis Shale

The Lewis Shale consists mainly of shale deposited in marine and coastal marine environments. There are numerous bentonite beds in the Lewis; the most prominent of these, the Huerfanito bentonite bed, roughly divides the Lewis into two depositional components. The lower half of the Lewis was deposited during overall transgression that began with deposition of the Cliff House Sandstone of the Mesaverde Group. The very basal part of the Lewis consists of interbedded thin sandstone and shale. This sandy sequence intertongues with the Cliff House Sandstone of the Mesaverde Group (fig. 3). The upper half was deposited during overall regression that resulted in deposition of the Pictured Cliffs Sandstone. The Lewis Shale intertongues with thin sandstone in the lower part of the Pictured Cliffs in much the same manner as the Mancos Shale does with the lower part of the Point Lookout Sandstone. The maximum flooding surface in the Lewis occcurs stratigraphically below the Huerfanito bentonite. This surface is marked by the presence of keeled planktonic foraminifera, suggesting water depths in excess of 300 ft (100 m) (Hutchinson and Kues, 1985).

The Lewis Shale consists of marine shale deposited during the last Cretaceous transgression in the San Juan Basin. Although commonly thought of as being deposited in deep water, where the Lewis grades landward into the Menefee Formation, Cliff House Sandstone, or Pictured Cliffs Sandstone (fig. 3), shallower water depositional environments should be encountered. The Lewis Shale is over 2400 ft (731.7 m) thick in the northern part of the basin (Molenaar, 1977; fig. 3). The upper 327 ft (99 m) of the Lewis below the Pictured Cliffs in the northern part of the basin has yielded mostly arenaceous benthic foraminifera (Carey, 1990) suggesting much shallower, nearshore environments for much of the upper Lewis. These data support the generally regressive nature for most of the Pictured Cliffs-Lewis couplet in the northern part of the basin.

A sedimentologic study of the Lewis Shale in the Bisti area, south of Farmington, New Mexico suggests that the marine shale and silt strata assigned to the Lewis represent upward

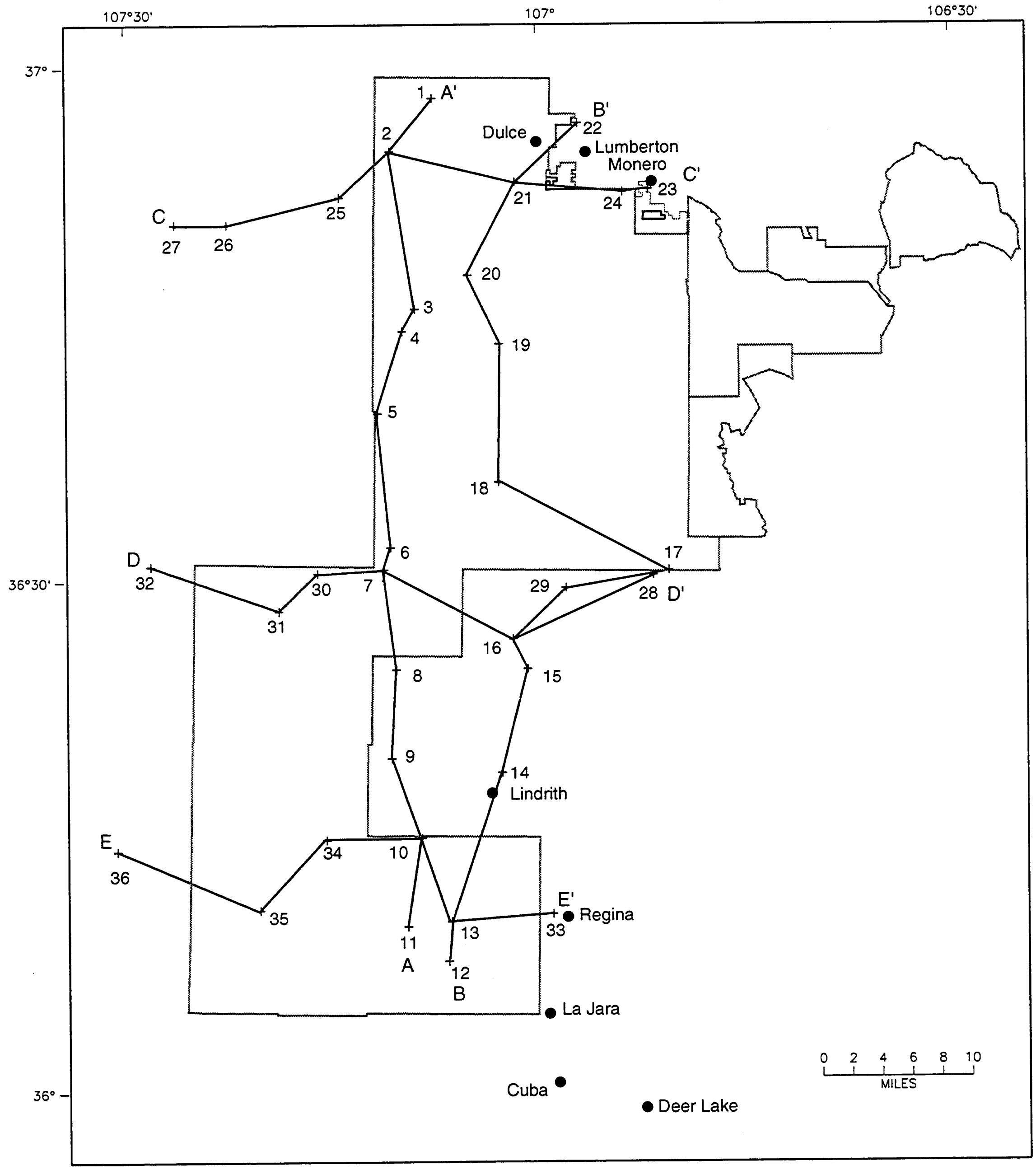


Figure 4. Map showing location of cross sections A-A', B-B', C-C', D'D', and E-E' (plates 1-5) with respect to the Jicarilla Apache Indian Reservation.

shoalling deposits; the marine units are gradationally overlain by delta-front silts and muds and distal mouth-bar sandstones (Hutchinson and Kues, 1985). At this locality the Lewis is only 69-112 ft (21-34 m) thick and it pinches out about 11.4 mi (19 km) to the west between the underlying transgressive Cliff House Sandstone and the overlying regressive Pictured Cliffs Sandstone (fig. 3). Foraminiferal assemblages recovered from the Lewis at Bisti are dominated by planktonics and calcareous benthics; their distribution coincides with the maximum westward transgression of the formation (Hutchinson and Kues, 1985) and are not indicative of nearshore paralic environments. Keeled planktonic foraminifera, normally indicating water depths >330 ft (100 m), are found to within a few feet below the Pictured Cliffs. The keeled planktonics found in the upper 10 ft (3 m) of the Lewis below the Pictured Cliffs could be reworked from below because the tests (shells) were abraded. However, one particular keeled planktonic species was not found below this horizon, suggesting that the enclosing mudstone was deposited in deep water.

METHODS OF STUDY

Several lines of study were implemented in order to define the facies, sequence stratigraphy, structural geology, hydrocarbon potential, and hydrocarbon-producing areas of the Mesaverde Group. As part of the phase one Mesaverde study, outcrops of the Mesaverde along the northeast side of the San Juan Basin were measured and described (Wright-Dunbar, 2000a). The Mesaverde Group at each outcrop section was subdivided into its formation components, facies were described, and the resulting stratigraphic succession was defined within a sequence stratigraphic model. At selected outcrops, gamma ray data were collected. The resultant data were reduced and synthetic gamma ray curves were constructed (Wright-Dunbar, 2000b). The synthetic curves were then related to facies described in the measured sections. The phase 2 subsurface component of the Mesaverde study, as covered in this report, integrated data, observations, and models constructed from the outcrop study with that obtained from wireline logs and drilling reports.

Numerous wireline logs were examined to determine tops of the geologic formations that comprise the Mesaverde Group. Five cross sections (2 south to north and 3 west to east) across the Reservation were constructed to show the stratigraphic relationships between the geologic formations within the Mesaverde Group as well as between the Mesaverde and the underlying Mancos Shale and overlying Lewis Shale (fig. 4; plates 1-5). The Juana Lopez Member of the Mancos Shale, considered to be nearly isochronous in the study area, was used as a datum. A discussion of the correlation of units with the Mancos Shale are reported elsewhere (Ridgley, 2000).

Only four cores from the Mesaverde Group were available for the thermal maturity and source rock characterization part of the study. All of the cores are in the Menefee Formation (fig. 5). Samples from the core were augmented with samples from the Menefee Formation at five outcrop measured sections (fig. 6 sections 2, 8, 9, 11, 12). Vitrinite reflectance or thermal alteration index data were obtained for coals or carbonaceous material from these cores and outcrops (table 1). These data were used to evaluate the thermal history of the Menefee Formation. Additionally, some coals or carbonaceous siltstone and shale from core and outcrop measured sections were sampled for Rock-Eval analysis in order to determine the hydrocarbon generative potential and thermal history of the Menefee.

A large digital tops database leased from IHS Energy Group was initially used to create a structure contour map on the base of the Bridge Creek Limestone Member of the Mancos Shale. The base of the Bridge Creek or top of the Graneros Shale, which represents either a bentonite

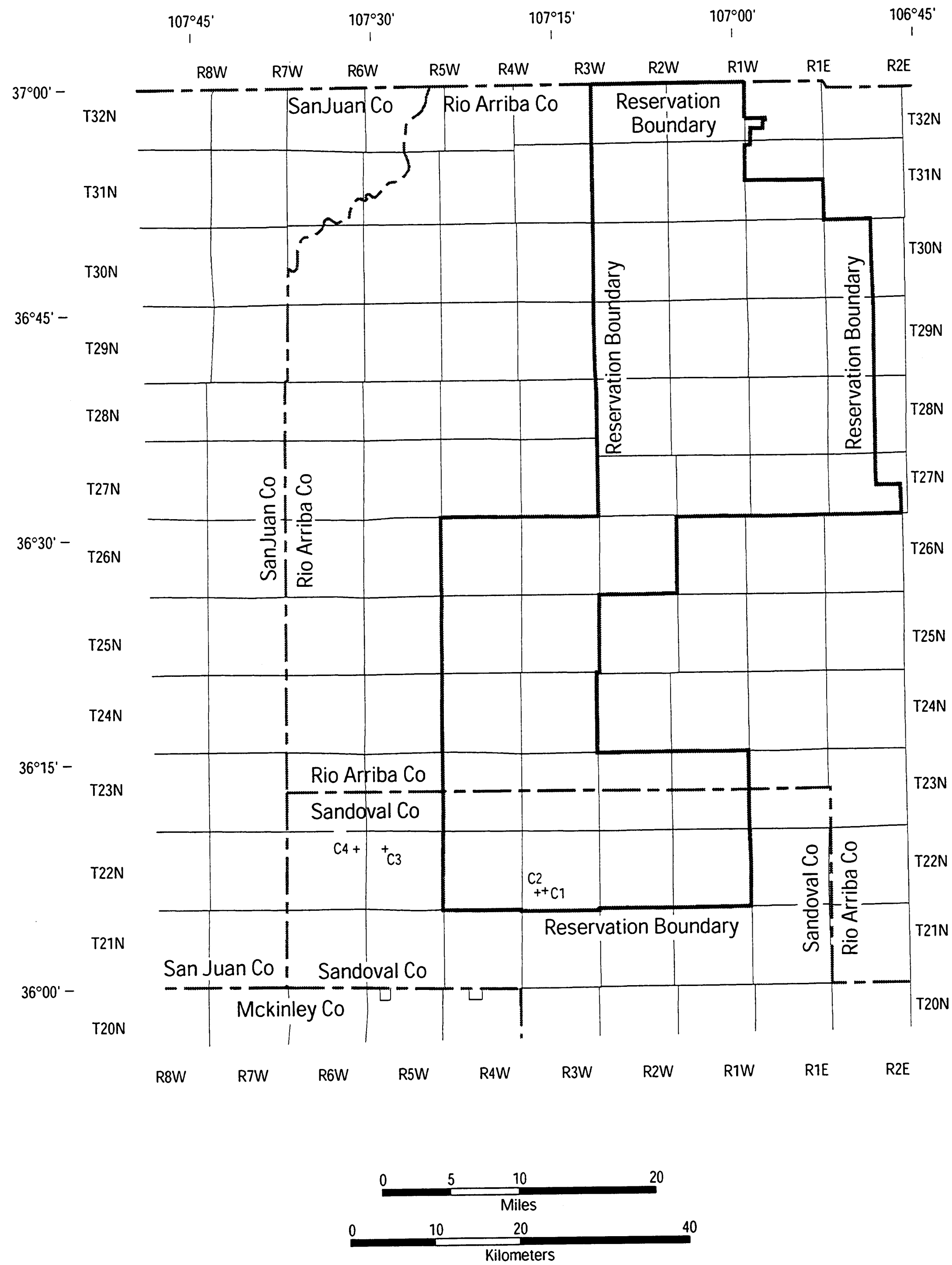
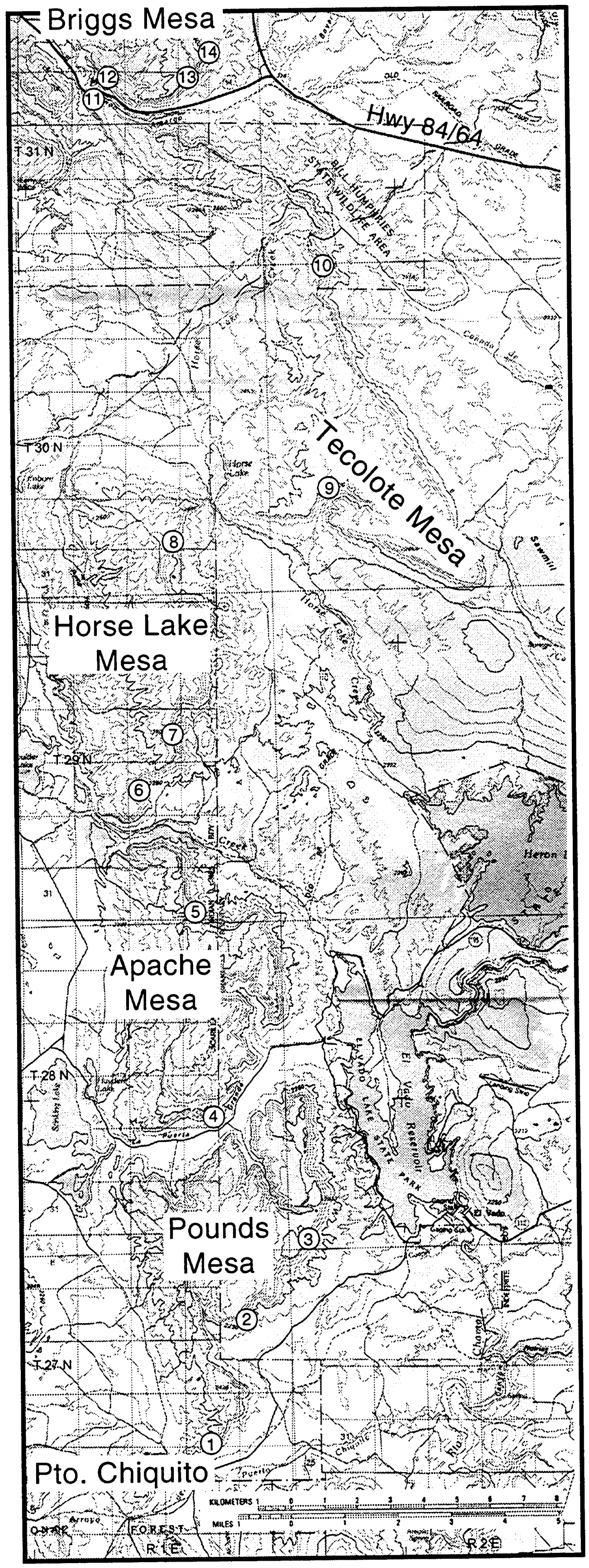


Figure 5. Map showing location of core (C1 - C4) in the Menefee Formation from which thermal alteration indices, or Rock-Eval pyrolysis analyses were obtained.

Figure 6. Base map of the outcrop study area from 1:100,000 Chama New Mexico-Colorado map showing major geographic localities and locations of measured sections 1 through 14 (circles). From Wright Dunbar (2000a).



bed or low-resistivity shale bed of undetermined composition, is considered to be a nearly isochronous unit throughout the area of the Jicarilla Reservation. However, there were too many spurious values for this datum in the database, because the same horizon was not consistently picked by drillers. Therefore, over 2550 wells on and near the Reservation were reexamined and the top of the Graneros Shale was manually picked and entered into a new database. From this database a new structure contour map was created (plate 6).

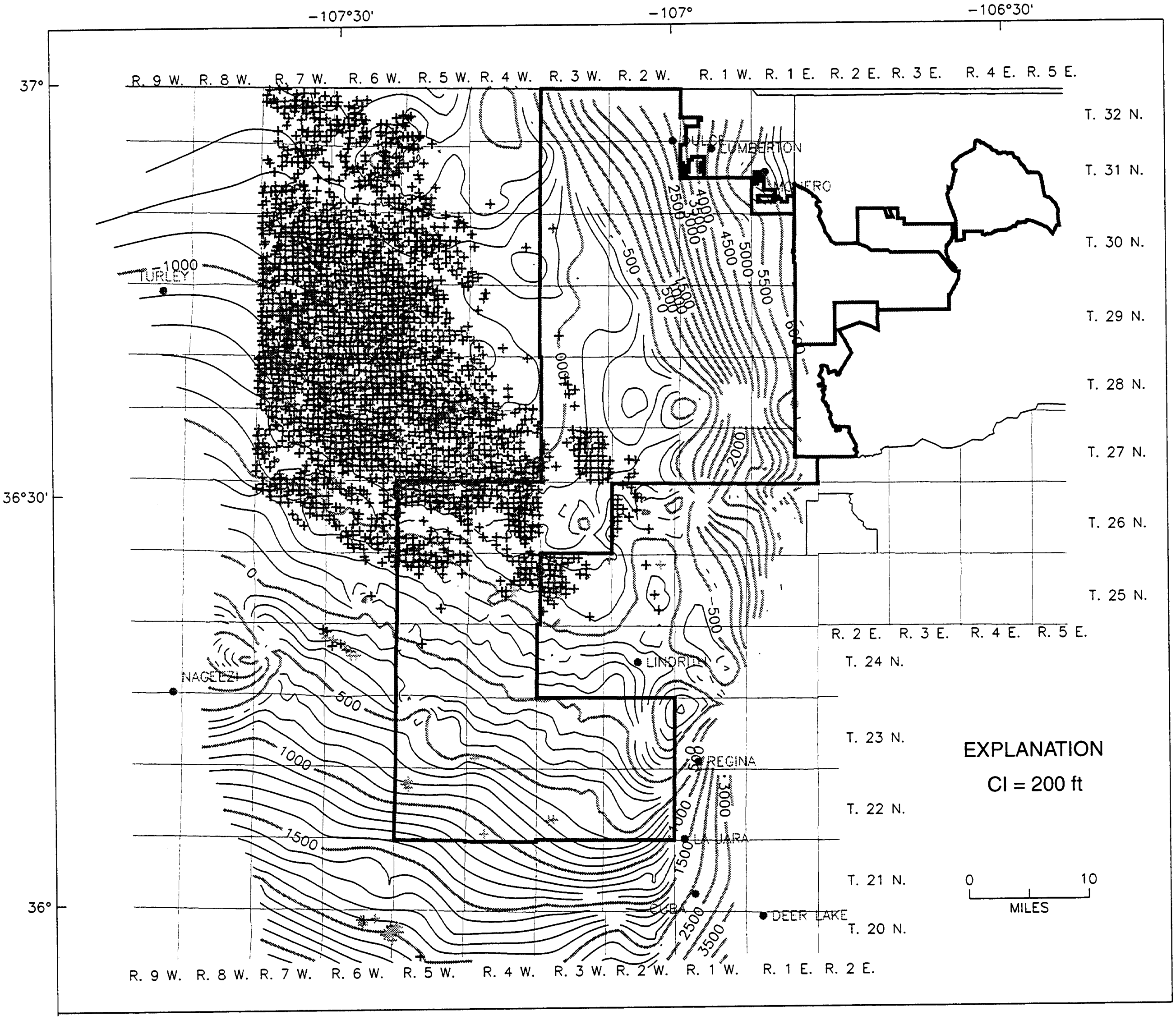
Production data from the Mesaverde Group and from its component formations, depending on how the data are reported, were extracted from the IHS Energy Group database. Data were obtained for both oil- and gas-producing fields. Data for the oil-producing wells were evaluated for assignment to the correct producing formation, and where necessary, producing wells were reassigned to the correct formation after evaluation of producing and perforated intervals. Data for gas-producing wells were not evaluated for assignment to the correct producing formation because of the large number of wells. These data were lumped as Mesaverde undivided. The data for oil and gas producing wells were plotted to show their spatial distribution with respect to structure and to each other (fig. 7). API oil gravities from the Mesaverde were also extracted from this database and their distribution plotted (fig. 8) to determine any regional trends. The API data were not separated by component formations of the Mesaverde.

Boundaries of seven oil and two gas fields in the Mesaverde (data from individual fields in Fassett, 1978) on and near the Reservation were compiled onto a base map (fig. 9). The spatial distributions of these fields were then used to evaluate the position of productive intervals, by field, within a sequence stratigraphic context and with respect to structure. Completion data for wells neighboring the fields were examined for: 1) test intervals in the Mesaverde and 2) the results of those tests. In extrapolating these intervals throughout the Reservation, it was hoped that areas and intervals in the Mesaverde Group that might contain by-passed oil resources would be highlighted.

STRUCTURAL GEOLOGY

The San Juan Basin is a semi-circular basin in northwest New Mexico and southwest Colorado that is bounded mostly by monoclinal uplifts. The basin has had a complex structural history; the final configuration of the basin was achieved during the Laramide orogeny in the Paleocene and Eocene (Woodward and Callender, 1977). The structural configuration of the northeast part of the basin in the vicinity of the Jicarilla Apache Indian Reservation basin is shown in plate 6. The deepest part of the San Juan Basin is often referred to as the central basin (fig. 1; plate 6). It is roughly elliptical in shape with the longest dimension oriented northwest-southeast and it straddles the Colorado-New Mexico border. The southwest part of the central basin is bordered by a northwest-southeast structural platform that dips gently to the northeast. This structural platform, known as the Chaco slope, is a regional structure upon which is superimposed a series of broad, low-amplitude folds that gently plunge to the northeast (plate 6). The northeast side of the basin is defined by a west-dipping monocline. This north-south monocline is defined by a set of west-verging and east-verging thrust or reverse faults (Taylor and Huffman, 2000).

The location of Mesaverde Group oil and gas fields on and near the Reservation with respect to structure is shown on figure 7. All of the Mesaverde oil fields are located along the Chaco slope. Some of these oil fields have associated gas, which generally is found in the structurally highest part of the field. Where the Chaco slope passes to the northeast into the central basin, hydrocarbon production is predominantly gas, although oil is also produced. Between the oil and gas production is a narrow zone where condensate is produced in conjunction with gas.



EXPLANATION

Mesaverde gas	Menefee-Point Lookout oil	Menefee-Point Lookout-Mancos oil
Point Lookout oil	Menefee oil	Mesaverde undefined oil

Figure 7. Map showing distribution of oil and gas producing wells on and adjacent to the Jicarilla Apache Indian Reservation superimposed on the regional structure. Structure contours drawn on the base of the Bridge Creek Limestone.

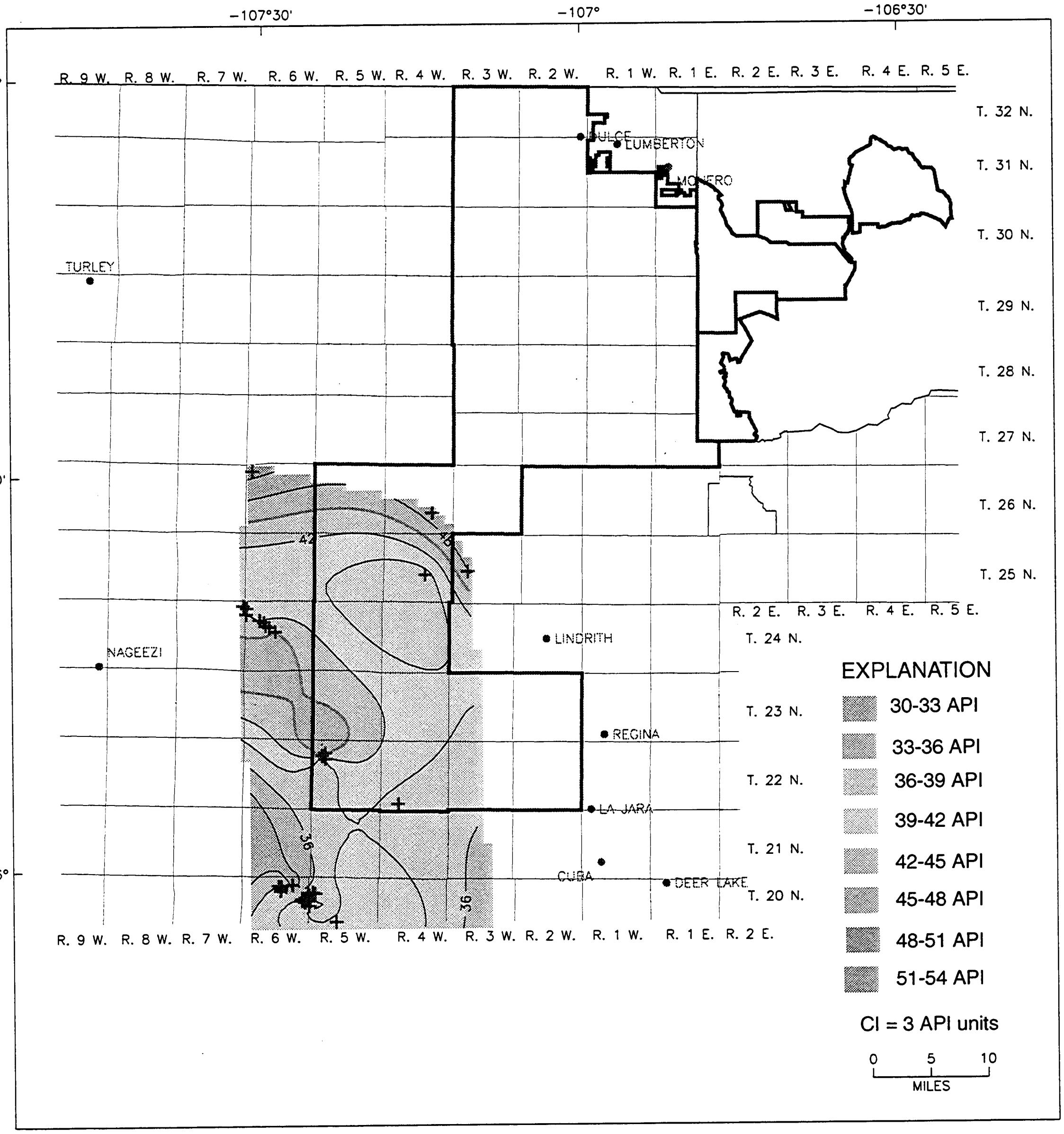


Figure 8. Contour map of API gravities from the Mesaverde Group in the northeastern part of the San Juan Basin.

SEQUENCE STRATIGRAPHY

A principal focus of the Mesaverde study was to subdivide the Mesaverde Group interval into its component formations using sequence stratigraphic principals and within these formations identify currently productive oil and gas facies as well as define potentially productive facies that have been overlooked by past drilling. The outcrop studies of the Mesaverde indicated the presence of two unconformities or sequence boundaries in the northern part of the study area, north of Township 28. The basal boundary occurs between the Point Lookout and the Menefee Formation in the northern part of the study area (Wright Dunbar, 2000a). The lower sequence boundary rises stratigraphically to the southwest where it is present only within the Menefee Formation. This sequence boundary incises more deeply to the northeast and actually cuts into shoreface sandstone of the Point Lookout. From south to north this surface sequentially cuts out fluvial deposits of the Menefee and shoreface sandstone of the Point Lookout (Wright Dunbar, 2000a). Strata overlying the sequence boundary are thus younger and genetically unrelated to rocks below the sequence boundary. The upper sequence boundary occurs only within the Menefee (Wright Dunbar, 2000a) and has not been defined in the southern part of the study area. In the northern part of the study area, the incised surface cuts deep channels in the Menefee. Younger and genetically unrelated fluvial and estuarine rocks fill these channels. Because the channel fill is depositionally similar to the underlying strata of the Menefee (especially in the northern part of the study area), detailed studies of the stratal stacking patterns are necessary in order to delineate the geometry of the second sequence boundary. However, both sequence boundaries appear to represent incised surfaces that locally have considerable relief, especially in the northern part of the study area where downcutting was more pronounced. The causes of base level lowering and the seaward shift of the deposition systems, resulting in bypass sedimentation, are not known at this time.

More recent studies of the Mesaverde and especially the Point Lookout Sandstone have focused on reevaluation of the depositional environments and the application of sequence stratigraphic principals (Wright, 1986; Devine, 1991; Katzman and Wright Dunbar, 1992; Wright Dunbar and others, 1992; Keighin and others, 1993; Wright Dunbar, 2000a). These studies provide the types of detailed information needed to determine the presence of internal unconformities or sequence boundaries. Application of these principals to the Point Lookout has resulted in the recognition of stacked fourth- and fifth-order cycles or parasequences within the overall regressive deposits (R. Zech, 1993, written commun.). The parasequences or parasequence sets consist of both regressive and transgressive components (Katzman and others, 1990; Devine, 1991). Katzman and others (1990) determined that transgressive deposits comprise an important part of each of each parasequence set. Inner shelf, back barrier, estuarine, and deltaic environments are recognized (Katzman and others, 1990; R. Zech, 1993, written commun.). Devine (1991) has suggested that transgressive estuarine deposits could potentially be important hydrocarbon reservoir facies.

The Point Lookout Sandstone is dominated by northwest-trending straight, strandplain and barrier coastlines. Straight strandplain coastlines are well preserved near Gallup, New Mexico. (Zech, 1982) as planar laminated, seaward dipping foreshore deposits. North from the Gallup area, foreshore deposits are less well preserved due to removal by later fluvial and tidal channels. Laterally, facies change from foreshore to tidal inlets and channels (Wright Dunbar and others, 1992) reflecting the changing dynamics of coastal processes and embayment of shorelines (Wright, 1986). Outcrop evaluation of the Point Lookout Sandstone as part of the phase one study (Wright Dunbar, 2000a) suggested the dominance of straight strandplain coastlines in the study area. At least six shorelines were identified (fig. 10).

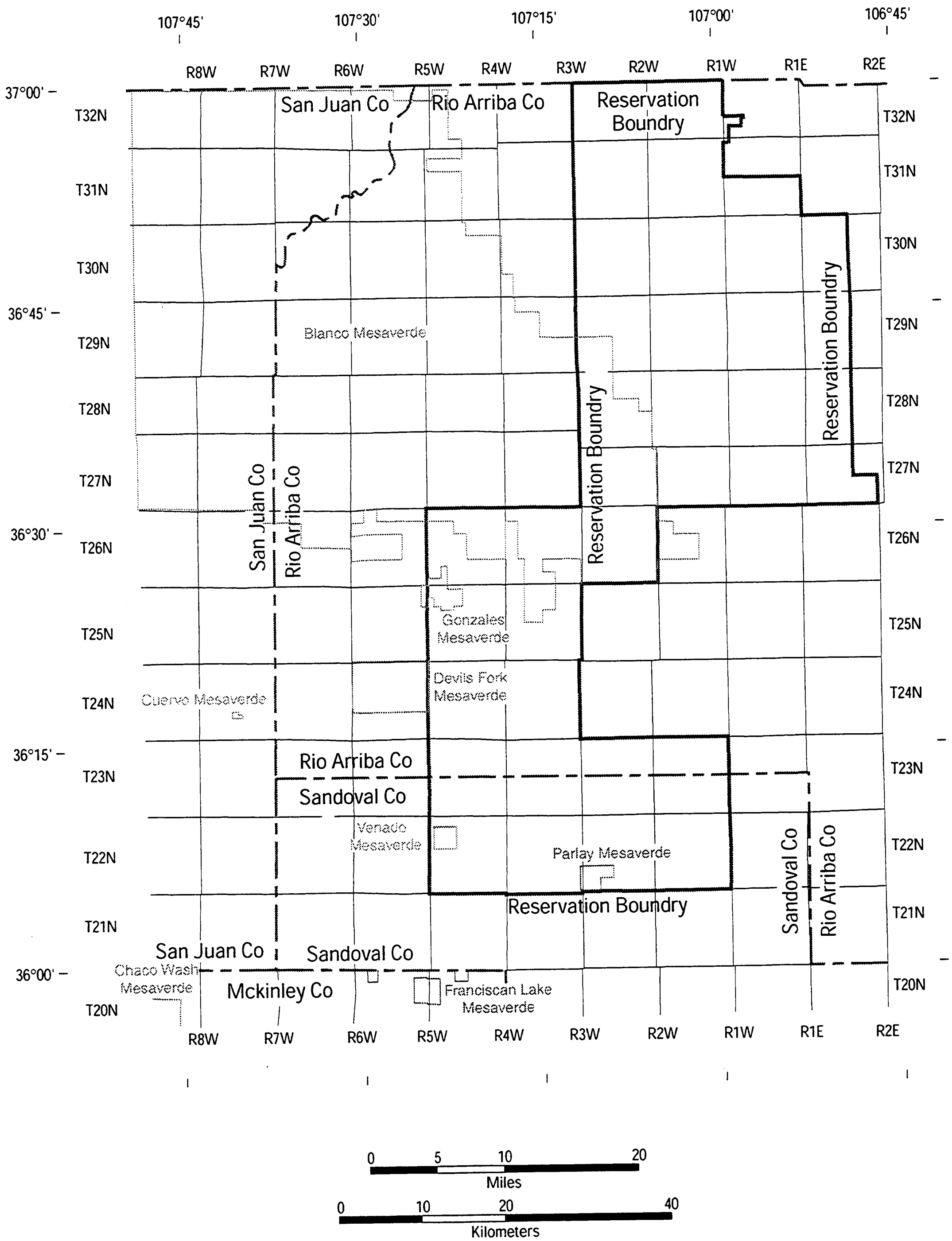
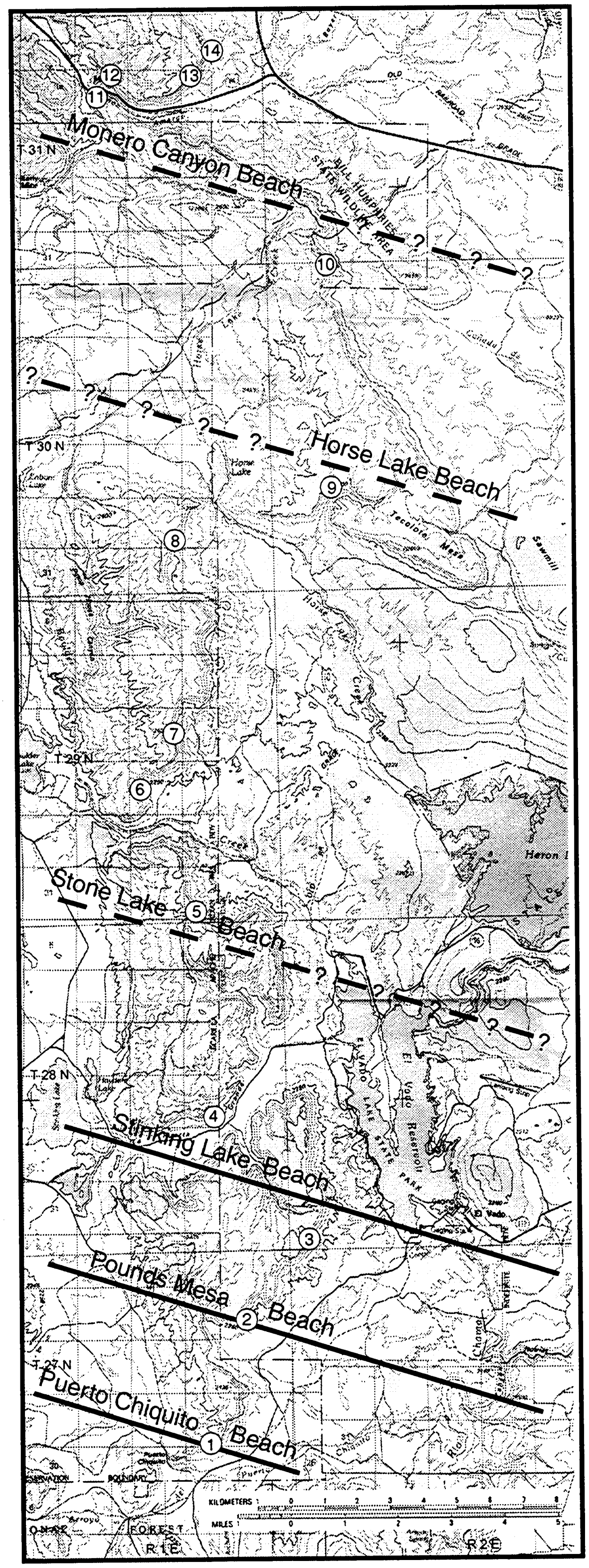


Figure 9. Map showing distribution of oil and gas fields in the Mesaverde Group on and adjacent to the Jicarilla Apache Indian Reservation (data from Fassett, 1978). Blanco Mesaverde and Gonzales Mesaverde are gas fields; remaining fields are oil fields.

Figure 10. Location of individual beach parasequences in the study area. Foreshore deposits constrain the location of the Puerto Chiquito, Pounds Mesa, and Stinking Lake shorelines. (Foreshore positon of North Llaves beach is located somewhere to the south of the study area, and is therefore not shown.) Position for Stone Lake, Horse Lake, and Monero Canyon beaches is inferred due to later erosion of foreshore and upper shoreface by the SB1 surface. From Wright Dunbar (2000a).



Although straight coastlines appear to be predominant in the Point Lookout, deltaic deposits are also a significant part of the rock record. Studies of the Point Lookout near Durango, Colorado indicate the presence of a large delta complex (Newman, 1982; Zech and Wright, 1989) that interrupted the otherwise straight coastline. In the Durango area, the transition from strandplain deposits to deltaic deposits was accompanied by a decrease in stratigraphic rise (Zech and Wright, 1989). The upper part of the deltaic strata overlies a previously unrecognized unconformity and reflects a more pronounced basinward shift in regressive depositional facies (Crandall, 1992; Wright Dunbar and others, 1992). This unconformity is also present in the study area. Rocks overlying the unconformity were deposited in estuarine environments and include bayhead delta sandstones, estuarine channel sandstones, and marine mudflat deposits (Wright Dunbar, 2000a).

The Menefee Formation in the study area has always been interpreted to represent deposition in nonmarine, fluvial settings (Fassett, 1977; Molenaar, 1977). New data by Wright Dunbar (2000a), however, suggests that estuarine rocks make up a significant component of the Menefee, especially in the northern part of the study area. Stacking patterns of fluvial sandstone, overbank mudstone, and thin coals in the Menefee show progressive changes laterally and vertically, reflecting the progressive progradation of the Mesaverde depositional system to the northeast. At least three stratal stacking patterns, from the base, to the top of the Menefee, have been observed at the surface (Wright Dunbar, 2000a) and in the subsurface (plates 1-5). Sandstones in basal Menefee strata are thin and difficult to correlate laterally. These sandstones occur lateral to buildups of the Point Lookout during periods of aggradation. The sandstone-mudstone sequences overlying the basal Menefee strata tend to be thicker (individual channels up to 2-3 times as thick as channels in the basal Menefee) and they are much easier to correlate. This middle sequence forms the bulk of the Menefee and represents deposition during major shifts of the shoreline to the northeast. The upper strata of the Menefee are characterized by thinner sandstone, mudstone and coal beds. This part of the Menefee was deposited during periods of transgression associated with backfilling of the incised surfaces and with the Lewis transgression. In the southern part of the study area, thin sandstones are found lateral to coastal marine sandstone of the Cliff House Sandstone. In the northern part of the study area, the Menefee Formation was deposited in both fluvial and estuarine environments. A more complete discussion of the geometry and nature of these rocks can be found in Wright Dunbar (2000a)

The Cliff House Sandstone was deposited as coastal marine sandstone during an overall rise in sea level. Thicker sandstone of the Cliff House consists of amalgamated sandstone deposited during periods of aggradation. Cliff House sandstones become younger to the southwest. The Cliff House was not observed at outcrop over much of the study area due to erosion. However, in the very northern part of the study area landward-stepping marine sandstones of the Cliff House pinch out updip into the Menefee (Wright Dunbar, 2000a). These sandstones are not laterally continuous with Cliff House sandstones to the southwest. This discontinuous nature of the Cliff House sandstones was observed in the subsurface (plates 1-5). In the subsurface, the position of sandstones assigned to the basal Cliff House Sandstone, north of Township 25, appears to be controlled by the infilling of the incised surface underlain by the upper sequence boundary (Wright Dunbar, 2000a).

Subsurface correlations of the Meseverde attempted to link outcrop observations, especially the location and orientation of the sequence boundaries, with wireline log responses. Two south-north cross sections A-A' and B-B' (fig. 4; plates 1 and 2) and three west-east cross sections E-E', D-D', and C-C' (fig 6; plates 3-5) through the Reservation show the results of the subdivision of the Mesaverde and the oil and gas producing intervals in the control wells. Given the limited amount of time for the subsurface Mesaverde study and the complexity of the depositional system defined at the outcrop, it was not possible to completely extrapolate outcrop observations to the subsurface. As a result, the subsurface correlations, principally define the boundaries between the Point Lookout Sandstone, Menefee Formation, and Cliff House sandstone. However, one incised surface in the Menefee Formation was noted in the subsurface correlations (plates 1, 2, 4, and 5, shown as dashed line). It is not clear exactly how this surface relates to the incised surfaces observed at the outcrop, however, it is recognized only in the northern half of the study area. The northern part of the study area is within the gas generation part of the basin. The sequence boundaries do not extend to the southern part of the basin where the potential oil reservoirs are found. The juxtaposition of facies across the sequence boundaries is not important in trapping oil because no oil occurs in the Mesaverde in this part of the basin. However, the spatial distribution of the facies can present barriers to efficient oil migration pathways because of the lateral discontinuities of sandstones and the elongation of these sandstones parallel to depositional strike rather than to depositional dip.

Additional studies of the Mesaverde in the subsurface are needed in order to work out the geometries of the depositional sequences observed at the outcrop. The new, detailed studies of the Mesaverde Group give us a better understanding of the lateral variability in depositional environments and facies. Recognition of this lateral variability and establishment of the criteria for separating deltaic from strandplain-barrier and estuarine deposits, and recognition of unconformities within the Mesaverde permit development of better hydrocarbon exploration models, because the sandstone geometry differs in each depositional system and across the unconformity. A more complete discussion of the sequence stratigraphy of the Mesaverde as observed at the outcrop in the study area and its application to potential hydrocarbon plays can be found in Wright Dunbar (2000a).

THERMAL MATURITY

Thermal maturity studies and time temperature modeling of Cretaceous rocks in the San Juan Basin document high levels of thermal maturity in the deep northern part of the basin (central basin) (Law, 1992). In their mapping of coal beds in the Fruitland Formation, Fassett and Hinds (1971) noted that the rank of these coals increased from southwest to northeast across the basin. The increase in coal rank was attributed to greater depth of burial in the northeast part of the basin. Heat from emplacement of the San Juan volcanics in the San Juan volcanic field in southern Colorado has also been suggested to be the principal cause for the higher thermal maturity of the coals in the northern part of the basin (Choate and Rightmire, 1982; Reiter and Clarkson, 1983a, 1983b; Reiter and Mansure, 1983; Bond, 1984; Meissner, 1984). Subsequent thermal maturity studies of coals from the Fruitland and Dakota Sandstone by Rice (1983) resulted in a basin thermal maturity pattern similar to that presented by Fassett and Hinds (1971). However, Rice attributed the higher thermal maturity of the coals in the northern part of the basin to a combined effect of greater depth of burial and higher geothermal gradient due to emplacement of the volcanics.

In a study using mean vitrinite reflectance (R_m) on coals and carbonaceous shales from core and cutttings from wells, Law (1992) found a similar thermal maturity pattern in the basin, except that he noted a small area of very high thermal maturity in the northeastern part of the basin (fig. 11). This area of higher thermal maturity was attributed to proximity to a series of northeast-trending dikes. Law's study not only focused on examining the lateral variation in thermal maturity but also looked at the change in thermal maturity in vertical profiles through 15 wells. Data from these profiles should permit a better interpretation of the effects of heat transfer process as well as examining the temporal changes in thermal regimes. Vertical vitrinite reflectance profiles from wells near the Reservation (Superior Sealy 1-7, sec. 7, T. 25 N., R. 6 W. and Sohio, Southern Ute 15-16, sec. 16, T. 32 N., R. 7 W.) are nonlinear and are composed of

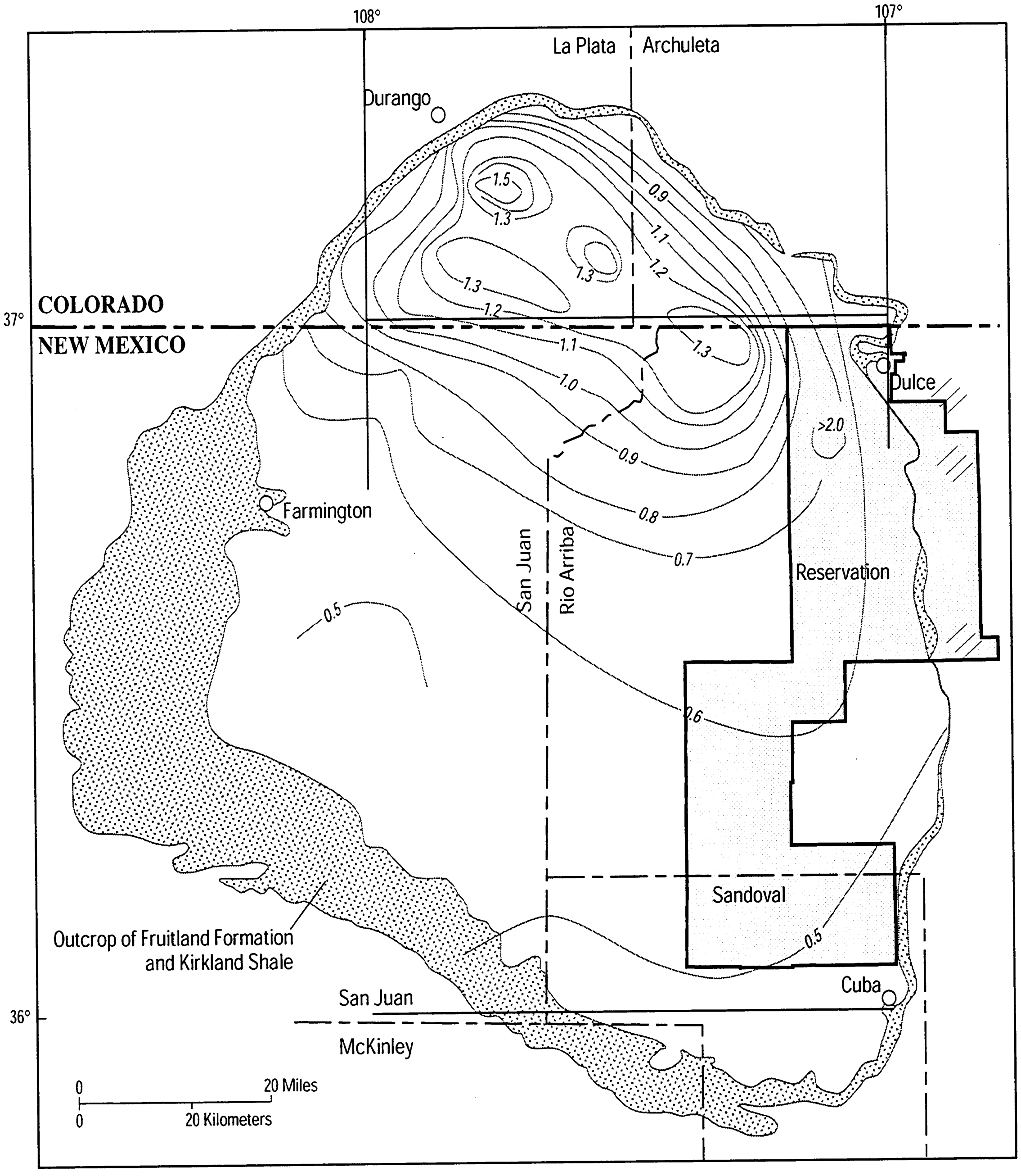


Figure 11. Thermal maturity map of the coal-bearing Fruitland Formation [modified from Fassett and Hinds (1971), Rice (1983) and Law (1992)] showing relative position of the isoreflectance contours to the Jicarilla Apache Indian Reservation. Contour interval, 0.1 % R_m. Hatchured areas show higher thermal maturity values based on vitrinite reflectance and thermal alteration indices in Menefee coals (table 1).

two or more linear segments having different slopes. The changes in slope suggest different processes acting on different sections of the rock column or to contrasting thermal conductivities. The steeper slopes were attributed either to pressure-induced vertically flowing fluids that formed in response to thermogenic hydrocarbon generation and generally coincided with a Rm of about 0.5 %, which is near the onset of catagenic hydrocarbon generation or to convective heat transfer associated with vertically flowing water. Time-temperature modeling (Law, 1992) suggested that if a major buried intrusion (source of heat) in the northern San Juan basin was responsible for the heat, the heating event took place about 20 to 40 m.y. ago (during Oligocene and Miocene). This is the time during which maximum burial was achieved and during which hydrocarbons would have been generated.

Vitrinite reflectance data from the Mancos shale (probably on carbonaceous material in cuttings) in Law (1992) indicate that most of the shale at least as far south as T. 22 N. and as far west as R. 6. W. are near or above a R_m of 0.5%, indicating the rock is mature enough to have started to produce oil (fig. 11). The R_m values in the Mancos increase to the north where they are well within the oil-generation window. The vitrinite thermal maturity map constructed using Fruitland and Dakota coals (fig. 11; Fassett and Hinds, 1971; Rice, 1983; and Law, 1992) shows that the isoreflectance lines should decrease in thermal maturity along the outcrop belt on the east side of the San Juan Basin. However, new vitrinite reflectance data from coals in the Menefee from the Horse Lake and Sulphur Canyon measured sections (fig. 6 sections 8 and 9), indicate that this is not the case (table 1). Rather, it suggests that the Menefee in this area is mature with respect to potential oil generation. Very carbonaceous sandstones from the Pounds Canyon and Monero Beach north measured sections (fig. 6 sections 2 and 12) contained no vitrinite, but the thermal alteration index stage (TAI) of these samples indicate high heat histories for these samples (table 1). The thermal alteration index is based on a progressive change in color of certain organic matter types (exinite, pollen and spore), each type having different responses to thermal increments (Staplin and others, 1982). TAIs were 4+ and 5 which are in the upper oil window, and condensate and wet gas stage. The cause of the high heat histories for the coals and carbonaceous sandstones along the outcrop belt on the northeast side of the basin is not known. However, it is possible that the dike swarm present to the west (Law, 1992) continues to the east in the subsurface, thereby locally raising the thermal gradient in this area.

Very carbonaceous sandstones and shales from core in the southern part of the study area yielded no vitrinite (table 1). Measured TAI values on spore and pollen range from 2.0 to 3.0. Samples in the 2.0 to 2.+ stage are immature with respect to oil generation; the TAI indices correspond to a R_o of 0.36 to 0.48. Samples from the 1-A Parlay and 2-A Parlay wells had TAI indices of 3.0 which is equivalent to an R_o about 0.5. An R_o of 0.5 is at the beginning of the oil window.

The past thermal maturity studies provide the framework for understanding the optimal time for hydrocarbon generation in the basin and where in the basin source rocks would be mature enough to generate hydrocarbons. Within and near the Reservation, studies that have examined the thermal maturity of the Menefee Formation, to determine whether it could be a source of some of the oil in Mesaverde reservoirs, i.e. self sourcing, are lacking. Most of the oil in the Mesaverde probably came from the Lewis Shale or from organic-rich shale layers in the Mesaverde as there is little evidence for communication between Mancos source rocks and Mesaverde sandstones, except where the basal Point Lookout intertongues with the Mancos. Upward leakage along faults is the only other avenue of potential communication. Otherwise the thick sandstones of the Point Lookout separate the Mancos Shale from the Lewis Shale and from all major sandstone reservoirs in the Mesaverde. No Lewis Shale samples were analyzed for their thermal maturity or organic matter type.

Table 1. Vitrinte reflectance maturity data on Menefee coals or carbonaceous material. Thermal alteration index (TAI) [Location of drill core shown in figure 5 and measured sections on topographic base map (fig. 6); m1, measured section; c1, drill core. Depth measured from the base upwards at outcrop measured sections and from the top down in core.]

Measured Section (m)or Drill Core (c)	Outcrop or Core Location	Depth/ft	Vitrinite Reflectance Maturity R_o	Comments
Horse Lake North[m8]	36°46'39"N, 106°49'43"W	276	1.43	Early condensate/wet gas stage
Sulphur Canyon[m9]	36°47'32"N, 106°46'26"W	350	0.91	Peak oil generation
Pounds Canyon[m2]	36°33'52"N, 106°48'16"W	191	1.9 R_o equivalent	No vitrinite. TAI 5 stage. Upper limit for oil, API gravity >50°
Monero Beach North[m12]	36°54'15"N, 106°51'04"W	175	1.6 R_o equivalent	No vitrinite. TAI 4+ stage. Condensate/wet gas stage.
1-A Parlay[c1]	Sec. 29, T. 22 N., R. 3W.	4210	0.5 R_o equivalent	TAI 3.0 stage
		4282.8	0.5 R_o equivalent	TAI 3.0 stage
2-A Parlay[c2]	Sec. 29, T. 22 N., R. 3W.	4296	0.46 R_o equivalent	TAI 3.0 stage
		4313	0.41 R_o equivalent	TAI 2+ stage
1-8 Jair[c3]	Sec. 8, T. 22 N., R. 5 W.	4026.4	0.37 R_o equivalent	TAI 2.0 stage
		4071.8	0.36 R_o equivalent	TAI 2.0 stage
1 Double Ought[c4]	Sec. 12, T. 22 N., R. 6W.	4060	0.48 R_o equivalent	TAI 2+ stage
		4083	0.42 R_o equivalent	TAI 2+ stage

Table 2. Rock-Eval data on coals and carbonaceous material from the Menefee Formation of the Mesaverde Group, San Juan Basin. [Locations of outcrop measured section ([m1]) and core ([c1]) are shown in figures 5 and 6 . Depth measured from the base upwards at outcrop measured sections and from the top down in core. TOC, total organic carbon (in weight percent); S_1, integral of first peak (existing hydrocarbons volatilized at 250°C for 5 minutes) (in milligrams per gram); S_2, integral of second peak (hydrocarbons produced by pyrolysis of solid matter (kerogen) between 250°C and 550°C) (in milligrams per gram); S_3, integral of third peak (CO_2 produced by pyrolysis of kerogen between 250°C and 390°C) (in milligrams per gram); T_{max}, temperature (°C) at which maximum yield of hydrocarbons occurs during pyrolysis of organic matter; PI, production index (S_1/S_1+S_2); HI, hydrogen index (S_2/TOC); OI, oxygen index (S_3/TOC).]

Measured Section or Drill Core	Outcrop or Core Location	Depth/ft	TOC	S1	S2	S3	S_1+S_2	T_{max}	HI	OI	PI
Sulphur Canyon [m9]	36°47'32"N, 106°46'26"W	290	73.29	6.74	90.19	22.75	96.93	429	123	31	0.07
Monero Road Cut[m11]	36°54'15"N, 106°51'04"W	56	10.07	0.67	15.66	3.92	16.33	435	156	39	0.04
2-A Parlay[c2]	Sec. 29, T. 22 N., R. 3W.	4313	13.04	1.64	28.48	0.92	30.12	430	218	7	0.15
1-8 Jair[c3]	Sec. 8, T. 22 N., R. 5 W	4071.6	4.21	0.38	5.88	0.55	6.26	441	140	13	0.16
1 Double Ought[c4]	Sec. 12, T. 22 N., R. 6W.	4060	5.89	0.21	5.06	0.64	5.27	441	86	11	0.14

Table 3. Pyrolysis parameters used to define source rock generative potential. [Parameters are defined in table 1.]

Quality	TOC (wt. %)[1]	S_1 (wt. %)[1]	S_2 (mg/g)[1]	S_2 (mg/g)[2]	S_2 S_1+S_2 (mg/g)[3]
Poor	0-0.5	0-0.5	0-2.5	0-2.2	<2
Fair	0.5-1	0.5-1	2.5-5	2.2-5.5	2-6
Good	1-2	1-2	5-10	>5.5	>6
Excellent	2+	2+	10+	>5.5	>6

[1] Peters (1986).
[2] Humble Laboratory (J. Espitalie, written commun., 1982).
3 Tissot and Welte (1984).

Although most of the thermal maturity studies focused on interpreting the vitrinite reflectance of the coals as a means to understand the thermal history of the basin and individual rock units, Rock-Eval data may also be used to interpret the thermal history of shale units which lack coal material. Rock-Eval pyrolysis measures the quantity, quality (type), and level of thermal maturation of organic matter contained in a rock. This technique alone is by no means the only way to evaluate a source rock, but, if used with an understanding of the limitations, it can be useful as a first screening tool and can yield a general characterization of the organic matter in a rock. In this study, representative chips of medium-gray to black shale from available cores in the Menefee and single samples of carbonaceous shale and coal from the outcrop were evaluated by Rock-Eval pyrolysis (Espitalie and others, 1977). The cores (fig. 5, table 2) are in the Menefee in the southern part of the Reservation and to the southwest of the Reservation and thus, provide some boundaries to thermal maturity levels that might be expected elsewhere on the Reservation.

Rock-Eval analyses of samples from the Menefee Formation are summarized in table 2. The total organic carbon (TOC) reported is the sum of the carbon in the pyrolyzate plus the carbon from the residual oxidized organic matter. The TOC values are relatively high (>4.0 percent); they appear to be well within the range of 1-3 percent required for oil generation and expulsion (Gries and others, 1997). The sample from Sulphur Canyon (table 2) is a coal and thus, high TOC values are expected. The samples from the Monero road cut and the 2-A Parlay well are very carbonaceous and may contain small amounts of coaly matter. The samples from the 1-8 Jair and 1 Double Ought wells are organic-rich shales. Hydrocarbon generation potential is estimated by the total pyrolytic hydrocarbon yield (sum of the S_1 and S_2 components). S_1 is the quantity of free hydrocarbons (HC) liberated by volatilization at 250° C and S_2 is the quantity of HC produced by further laboratory heating of kerogen. Both S_1 and S_2 are reported in mg HC/g rock. Several generative potential schemes using Rock-Eval analyses have been proposed (table 3). Mostly commonly used is the sum of the S_1 and S_2 components (Tissot and Welte; 1984). As shown in table 2, the generative potential of Menefee Formation coal and carbonaceous shale samples collected exceed 5.0 mg HC/g indicating a fair to excellent potential to generate liquid hydrocarbons.

Another measure related to the quantity of pyrolyzable organic matter or hydrocarbons is the hydrogen index (HI), defined as the S_2 yield (remaining hydrocarbon-generating capacity of the organic matter) normalized by total organic carbon. The hydrogen index is also useful in describing the type of organic matter present in a rock and the type of hydrocarbons that will be ultimately generated. Hydrogen index values (in mg HC/g $C_{organic}$) of 0-150 yield mostly gas, of 150-300 yield gas and oil, and greater than 300 yield mostly oil (Peters, 1986). The most widely used graphical tool for defining the type of organic matter contained in a source rock is the modified van Krevelen diagram. This diagram is a plot of the hydrogen index (HI) and the oxygen index (OI) (S_2 and S_3 normalized by total organic carbon respectively), and gives an indication of the type of organic matter (types I, II, III) and the degree of thermal evolution. Type I organic matter is hydrogen rich (sapropelic or lipid rich), is present primarily in marine and lacustrine rocks, and generates mainly oil during catagenesis. Type II organic matter is generally present in marine rocks, and generates oil and gas during catagenesis. Type III kerogen is oxygen rich and hydrogen poor (huminite and vitrinite), is present mainly in terrestrial, marginal-lacustrine, or marginal-marine rocks, and generates mostly gas during catagenesis.

Figure 12 is a modified van Krevelen diagram comparing the HI to OI of the samples (table 2) from the Rock-Eval pyrolysis assay. Using the criteria set forth above, there appear to be two principal organic matter types. Two of the five samples have HI greater than 150 and less than 300. This is indicative of mixed type I and type II organic matter. These rocks would be expected to produce a mixture of oil and gas. The other three samples had a HI less than 150 indicative of type III organic matter; this rock would be expected to produce gas.

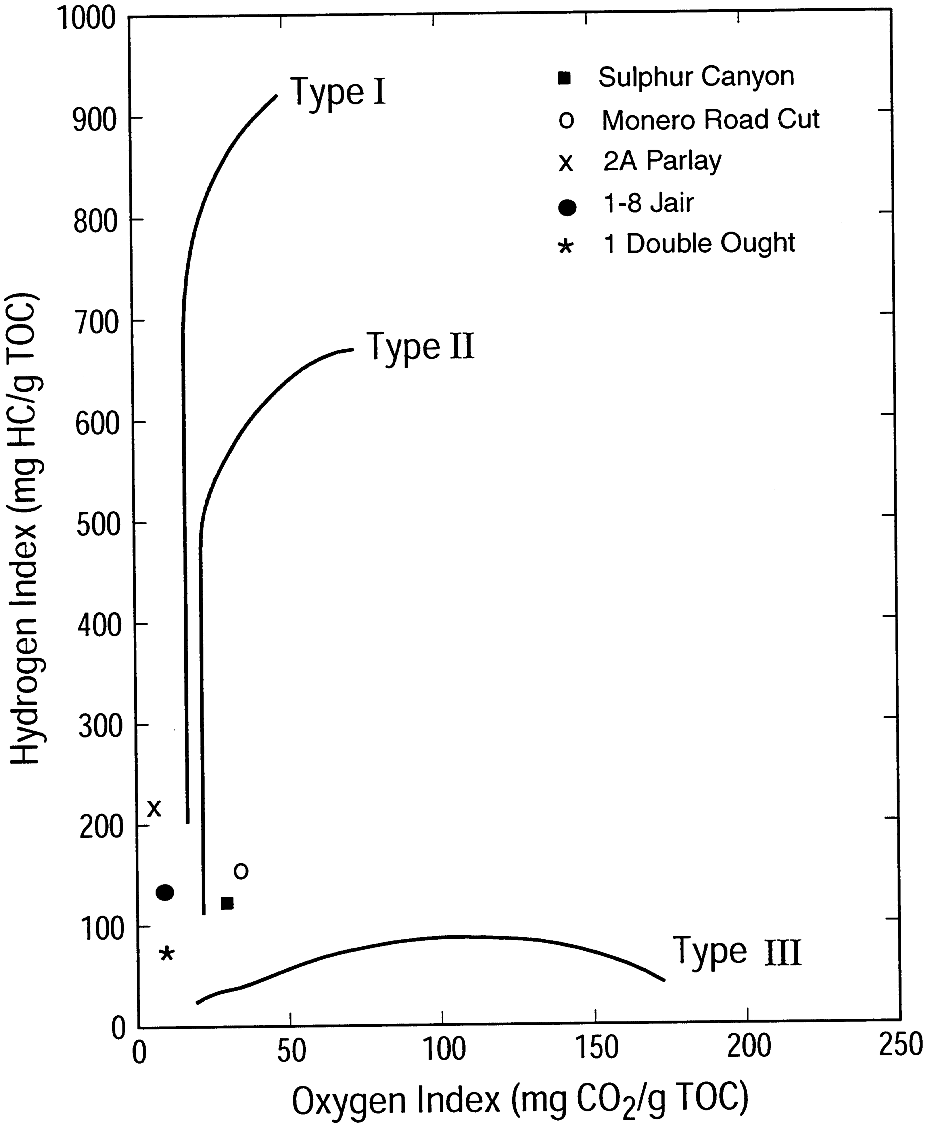


Figure 12. Plot of hydrogen index (HI) versus oxygen index (OI) on a modified Van Krevlin diagram from Rock-Eval pyrolysis of rock chips from the Menefee Formation. Samples are separated by outcrop measured section and core.

Rock-Eval data can also be used as evidence of thermal maturity. One thermal maturity indicator is the production index (PI) or transformation ratio. Production index is defined as the ratio of volatile hydrocarbon yield to total hydrocarbon yield $S_1/(S_1 + S_2)$. The transition from immature to mature, or beginning of the oil window, is about PI=0.10, and the end of the oil window is about PI=0.50 (Tissot and Welte, 1984). Two samples (table 2) have PI less than 0.1 which suggests that they are immature to marginally mature with respect to hydrocarbon generation. The remaining samples have PI greater than 0.1 indicating maturity within the oil window.

One other thermal maturity indicator obtained from Rock-Eval data is T_{max} which is the temperature at which maximum yield of hydrocarbons occurs during pyrolysis or, in other words, the temperature at which the S_2 peak occurs. The onset of oil generation (transition from immature to mature) is considered to occur at a T_{max} of 430°C (Humble Laboratory, 1993, based on written communication from J. Espitalie, 1982) or 435°C (Tissot and Welte, 1984). The upper limit of oil generation occurs at about 460°C (Tissot and Welte, 1984). Peters (1986) suggested that the analytical error of a measured T_{max} is commonly from 1° - 3° C. As shown in table 1, the T_{max} for three samples is at or above 435° C, placing the samples within the oil generation window.

The thermal maturity data for the Menefee suggest that organic matter in the northeast part of the basin reached maturity levels for oil and wet gas generation. In contrast thermal maturity data from the Menefee for the southern part of the study area (and the Reservation) is equivocal. T_{max} data suggest that some samples are within the oil generation window, whereas TAI values suggest that they are not. Only a few samples of the Menefee were analyzed, hence, extrapolation of the results are tenuous. However, the results indicate that additional samples of the Menefee should be analyzed, because the findings could be extrapolated to better understand the thermal maturity of the Lewis Shale. Core is generally unavailable for the Lewis.

OIL AND GAS FIELDS

There are 24 small oil fields in the Mesaverde (Fassett, 1991) in the San Juan Basin; these have an aggregate cumulative production of less than 2 MMBO. All but one of the oil fields are located on the Chaco slope in the southeast part of the basin and all the fields are defined by a small number of wells. Most of the oil fields are found to the west and south of the study area. Oil production from these fields occurs mostly in isolated channel sandstones in the Menefee Formation. Production is mainly from stratigraphic traps. There is some production from shoreface sandstone of the Point Lookout Sandstone or from combined Point Lookout and the transition sandstone-mudstone sequence of the upper Mancos Shale. In a few wells, perforated intervals extend from the Menefee into the top of the Mancos, and oil production is reported as coming from the entire interval.

For this study, seven oil fields and two gas fields (fig. 9) on and near the Jicarilla Apache Indian Reservation were evaluated with respect to the sequence stratigraphic model that has been constructed for Mesaverde. The principal reason for this evaluation was to determine currently producing facies and the areal extent of production from these facies within field boundaries. This spatial distribution could then be used to highlight areas where similar facies are present but from which there is no current production. The field name, location, type of hydrocarbon production, type of drive, field API gravity, producing interval, and structural setting for each oil and gas field are listed in table 4. Data for the fields were taken from individual field descriptions in Fassett (1978); references for individual field descriptions are also in table 4 and will not be repeated below. Observations as to producing intervals and field boundaries are from field descriptions in Fassett (1978); these have not been updated since the original descriptions. However, the contacts as shown on the cross sections (plates 1-5) between the various productive intervals discussed below can be used in conjunction with data available for individual wells drilled since the original descriptions to expand our knowledge of currently productive units. The distribution of oil and gas producing wells with respect to structure are shown in figure 7. API gravities were available for a limited number of wells. A plot of the distribution of the API gravities shows that the oils become somewhat heavier from northeast to southwest (fig. 8).

Characteristics of individual oil fields will be discussed briefly from oldest to youngest producing intervals. Cumulative production of oil, gas, and water for the fields listed in table 4 indicate that some of the oil fields are no longer producing and others only have production from a few wells (proprietary data in IHS Energy data base). Of the seven oil fields evaluated, only the Franciscan Lake Mesaverde oil field (fig. 9) produces from combined fluvial sandstone of the Menefee and shoreface sandstone of the Point Lookout Sandstone (table 4). Production from the Menefee is in noncorrelative sandstones at slightly different stratigraphic intervals. Production from the Point Lookout is also from different stratigraphic intervals. Total oil production has been slightly less than 570,000 barrels of oil. Most wells in the field are inactive. There is some associated gas produced with the oil. Production in the Franciscan Lakes field is in stratigraphic traps with minor structural closure. The field is located on a broad northeast-dipping anticline that is superimposed on the broad northwest-southeast trending structures of the Chaco slope (fig. 13; table 4).

The Cuervo Mesaverde and Devils Fork Mesaverde oil fields (fig. 9; table 4) produce only from the Point Lookout Sandstone. Both oil fields are located on broad northeast-dipping flexures that are superimposed on the broad northwest-southeast trending Chaco slope (fig. 13; plate 6). Both fields appear to produce from upper Point Lookout sandstone that is interbedded with mudstone and thus, production is from stratigraphic traps. Oil production from the Cuervo Mesaverde field has been less than 60,000 barrels of oil, whereas oil production from the Point Lookout Sandstone in the Devil's Fork field has exceeded 415,000 barrels.

Oil is produced from isolated sandstone channels in the Menefee Formation in the Chaco Wash Mesaverde, Parlay Mesaverde, Rusty Mesaverde, and Vendao Mesaverde (fig. 9; table 4). In the Chaco Wash Mesaverde field, over 29,000 barrels of oil has been produced from a single fluvial channel sandstone. The channel is aligned with the structural nose of a broad doubly-plunging antincline that dips to the northeast (fig. 13). Thus, oil production is from a combined structural and stratigraphic trap. Oil production in the Parlay Mesaverde field is from an isolated fluvial channel sandstone in the Menefee Formation that is draped over a north-dipping flexural bend in the regional structure (fig. 13). Over 103,000 barrels of oil has been produced from a combined structural and stratigraphic trap. Production in the Rusty Mesaverde oil field (table 4) was limited to one well that no longer produces. Oil was produced from isolated sandstone in the Menefee; 8695 barrels of oil was produced. The well was located on the broad northwest-southeast-trending Chaco slope; production was from a stratigraphic trap. Three wells define the Venado Mesaverde oil field (fig. 9; table 4). Each well produces from a different sandstone channel in the Menefee. Production is from stratigraphic traps located on the gently northeast-dipping flexures of the Chaco slope. Combined, oil production from the three different fluvial sandstones has exceeded 96,000 barrels.

Despite the excellent reservoir nature of the Mesaverde sandstones and the presence of abundant stratigraphic traps, the Mesaverde does not host any significant oil fields (Fassett, 1991). If there was any significant oil to be found in the Mesaverde, most likely it would have been found by now as there are hundreds of wells that have been drilled through the oil producing part of the Chaco slope. Examination of a random selection of wells that drilled and tested the Mesaverde and did not find oil suggests that the

Table 4. Location and producing characteristics of oil and gas fields in the Mesaverde Group on and near the Jicarilla Apache Indian Reservation.

Field Name	Location	Type of Hydrocarbon Production	Type of Drive	Field API Gravity	Producing Formation	Structural Setting
Chaco Wash Mesaverde[1]	T. 20 N., R. 9 W.	Oil	Low pressure water drive	46°	Menefee	Broad double NE--plunging anticline
Cuervo Mesaverde[2]	T. 24 N., R. 8 W.	Oil	Fluid expansion	38°	Point Lookout Sandstone	Broad NE-dipping flexure in the NW-SE regional structure
Devils Fork Mesaverde[3]	T. 24 N., R. 6W.	Oil	Solution gas	42°	Point Lookout Sandstone	Broad NE-dipping flexure in the NW-SE regional structure
Franciscan Lake Mesaverde[4]	T. 20 N., R. 5-6 W.	Oil	Fluid expansion and water drive	42°	Menefee and Point Lookout	Broad NE-dipping anticline on the NW-SE regional structure
Gonzalez Mesaverde[5]	T. 25-26 N., R. 5-6 W.	Gas	Solution gas	38.5°	Menefee and Point Lookout	Broad NE-dipping flexure on NW-SE regional structure
Parlay Mesaverde[6]	T. 22 N., R. 3 W.	Oil	Solution gas, minor gas cap expansion	44.2°	Menefee	Broad north-dipping flexure in the NW-SE regional strcuture
Rusty Menefee[7]	T. 22 N., R. 7 W.	Oil	No data		Menefee	Broad flexure in the NW-SE regional structure
Venado Mesaverde[8]	T. 22 N., R. 5 W.	Oil	Gravity flow	46°	Menefee	E-W regional structure
Blanco Mesaverde[9]	T. 25-32 N., R. 2 -13 W.	Gas/minor oil	Gas expansion	33-60°	Point Lookout, Menefee, Cliff House	Broad, low-amplitude folds on NW-SE regional structure

[1] Black, B. A., Chaco Wash Mesaverde, in Fassett (1978), p. 260-262.
[2] Dugan, T., and Fagrelius, K., Cuervo Mesaverde, in Fassett (1978), p. 274-275.
[3] Dunn, S.S., Devils Fork Mesaverde, in Fassett (1978), p. 279-281.
[4] Kennedy, C.C., Franciscan Lake Mesaverde, in Fassett (1978), p. 304-306.
[5] Pritchard, R.L., Gonzales Mesaverde, in Fassett (1978), p. 325-326.
[6] Gray, G.H., Parlay Mesaverde, in Fassett (1978), p. 453-455.
[7] Kennedy, C.C., Rusty Menefee, in Fassett (1978), p. 477-479.
[8] Pritchard, R.L., Venado Mesaverde, in Fassett (1978), p. 548-549.
[9] Pritchard, R.L, Blanco Mesaverde, in Fassett (1978), p. 222-224.

conventional oil traps (stratigraphic or structural) are local in extent, and thus, may be more difficult to find. The reasons for the lack of oil occurrences in conventional traps are not entirely clear. However, there are several possible explanations to this enigma. One explanation is the lack of appropriate source rock. Fassett (1991) has suggested that the sources of Mesaverde oil were the organic-rich carbonaceous shales found mostly in the Menefee Formation. It is also possible that Menefee coals could also have sourced the oil found in isolated sandstone reservoirs of the Menefee. Coals in the Fruitland Formation are thought to be the source of small quantities of oil found in Fruitland sandstones (Rice and others, 1989; Clayton and others, 1991). Limited studies of the potential source rock character of the Lewis Shale suggest that it is composed mostly of type III kerogen (Rice and others, 1989), and thus, it would generate gas or wet gas if fractionation occurred or if small amounts of type I or II matter were available. The Lewis Shale interfingers with and lies lateral to the formations composing the Mesaverde Group. As such it is the only other likely source of potential oil and gas in the Mesaverde. Additional source rock characterization studies of the Lewis Shale, especially from the areas where it is not in close proximity to Mesaverde shorelines, are necessary before its potential to generate oil is completely understood.

Another possible reason for the lack of major oil accumulations in the Mesaverde is that most of the oil migrated updip from the central basin to the south and was reservoired in rocks that have been removed by erosion. The Mesaverde is absent over areas in the southern part of the San Juan Basin. There is a general lack of structures on the Chaco slope (plate 6) that would permit trapping of oil in quality sandstone reservoirs along migration pathways extending from the deeper, more mature part of the central basin onto the Chaco slope. Most of the Mesaverde oil fields, although small in size, are clustered on the northern margin of the Chaco slope. If any long distance oil migration did occur and if intermediate structural traps were absent (as in this case), the oil would have migrated to the updip part of the Chaco slope. Unfortunately, the Mesaverde has been removed from this area in the southeastern part of the San Juan Basin to test this hypothesis. This explanation is not entirely satisfactory in explaining the lack of oil in the Mesaverde, because there are numerous stratigraphic traps along possible migration pathways that should contain oil, if it had been generated. These traps include isolated sandstone channels in the Menefee (a few of which do produce oil), pinchout of distal toes of Point Lookout shoreface sandstone into marine mudstone of the Mancos Shale, and pinchout of the Cliff House Sandstone into the Menefee Formation. The lack of oil in the Mesaverde is most likely related to one or a combination of the following: 1) lack of abundant organic matter of the type I or II variety in the Lewis Shale, 2) ineffective migration pathways due to discontinuities in sandstone reservoir geometries, or 3) cementation or early formation of gas prior to oil generation that reduced effective permeabilities and served as barriers to updip migration of oil.

The Blanco Mesaverde field (fig. 9; table 4) produces the bulk of the gas found in the Mesaverde and all gas produced from this field is from the central basin (plate 6). Condensate (?, reported as oil in the IHS Energy database) is also produced from the Blanco field. The Blanco field is categorized as a gas field, although over 40 million barrels of condensate have been produced. Over two-thirds of the 6327 wells completed in the Mesaverde (active and inactive, IHS Energy Group, June 2000) have produced some condensate and water. However, most condensate production is low compared to gas production on a per well basis. Wells that produce or have produced condensate and water are fairly evenly distributed throughout the Blanco field, indicating that future wells completed in the Blanco field are likely to produce some condensate and water. The relation of the condensate to gas is not known. It has not been determined if the Blanco field at one time was a large *in situ* unconventional oil field that subsequently has been cracked to gas or whether the small quantities of condensate (per well) are a by-product of gas generation that has passed through the oil window. The kerogen types from Rock-eval analysis (table 1) indicate that mostly gas should be produced.

Gas is produced from the Point Lookout, Menefee Formation, and where present, the Cliff House Sandstone. Gas production is neither stratigraphically nor structurally controlled (figs. 7 and 13); the field covers a variety of structural settings within the deep central basin. The gas field lacks a regional water drive; water production is local, but pervasive throughout the field (see discussion in Fassett, 1978). Field growth has been by step out drilling. Over 10 trillion cubic feet of gas has been produced from the Blanco Mesaverde field. The Gonzales Mesaverde gas field (fig. 9; table 4) is located just south of the Blanco Mesaverde gas field. Production characteristics are similar to the Blanco Mesaverde field and the Gonzales Mesaverde gas field could be considered an extension of Blanco Mesaverde field. Gas production is from lenticular channel sandstone in the Menefee and from beach and bar sandstone of the Point Lookout Sandstone. Structurally, the field is located on broad northeast-dipping flexures of the Chaco slope (fig. 13). There is no separate gas production reported for this field; it is likele that gas production is reported as occurring with the Blanco Mesaverde field.

There is no obvious seal that defines the spatial distribution of the gas in the Mesaverde. Several trapping mechanisms for the gas have been proposed. Berry (1959) suggested that gas was trapped by updip hydrodynamic forces induced as a result of erosion. As a result of the erosion, the rocks became underpressured eventually allowing water to migrate downdip on the basin margins. A variant on this thesis is that the gas accumulation is characteristic of basin-centered gas accumulations. This type of accumulation fits the "continuous-type" gas accumulation category that was first defined and used in the 1995 USGS national assessment (Schmoker, 1995). Continuous-type accumulations are considered to be large, low grade (initial volumes), unconventionally reservoired (i.e. no downdip water contact) accumulations that crosscut lithologic boundaries. They might require different development strategies from those used in conventionally reservoired gas accumulations (Schmoker, 1995). Where they occur, continuous-type gas accumulations are thought to be everywhere gas-charged in the gas-bearing interval, although the gas may not always be economic. Other characteristics of continuous-type gas accumulations include an updip water contact (i.e. the gas accumulation is located downdip from water-saturated rocks), the insignificance of conventional traps and seals, a close association of reservoir with source rock, abnormal pressures (high or low), and low reservoir permeability in facies that have large areal extent. Reservoirs include sandstone, siltstone, shale, chalk, and coal. Although characterized by large in-place hydrocarbon volumes, production is characterized by low recovery; however, individual wells may produce for a long time. Production rates are heterogeneous (Schmoker, 1995).

Another mechanism suggested for trapping Mesaverde gas is the formation of secondary kaolinite which contributed to loss of porosity and permeability, thus, inhibiting long distance migration (Cumella, 1981). Stratigraphic traps were viewed by Cumella (1981) and Fassett (1991) as the principal mechanisms for trapping gas. Fassett suggested that many of the sandstones, including those that comprise the Point Lookout are laterally discontinuous and are separated my mudstone layers that provide permeability barriers. The discontinuities in sandstone geometries are related to juxtaposition of different depositional environments (Fassett, 1991; Wright Dunbar, 2000a). The lateral discontinuities in sandstone geometry may also have been a factor in inefficient oil expulsion (assuming oil was produced in significant amounts) as they would not provide interconnected conduits for migration. Fassett (1991) suggested that gas did migrate updip where there was interconnected permeable sandstone, but that this gas has since escaped. Subsequently, water moved down dip through the permeable layers.

The Point Lookout Sandstone is host for significant gas resources in the deep, northern part of the San Juan Basin (Hollenshead and Pritchard, 1961; Huffman, 1987). Recent petrographic evaluations of the Point Lookout in core (Keighin and others, 1993) and at the outcrop (Hicks, 1991) examine the parameters that affect reservoir quality. The results suggest that measured permeabilities are, in part, facies controlled and in part controlled by effective porosity. The best reservoir quality sandstones have the highest permeabilities and most effective porosities and are found in upper shoreface and shoreface/delta front environments where sorting is better and cementation is less (Keighin and others, 1993). Lower permeabilities were observed in samples that are more extensively cemented by calcite; these samples are typically from middle and lower shoreface environments (Keighin and others, 1993). Primary porosity is enhanced by dissolution of mineral grains, and secondary porosity, which occurs as microporosity, is enhanced by partial leaching of rock fragments, growth of clays, or by dissolution of an earlier authigenic mineral phase. Cementation by calcite reduced both effective permeability and porosity (Keighin and others, 1993). In the northeast part of the San Juan Basin, average porosities in Point Lookout sandstones are from 10 to 15 percent and permeabilities range from 0 to 5.5 millidarcies (Pritchard, 1978).

It is clear from the forgoing discussion that there is disagreement on the controls on the distribution of hydrocarbons in the Mesaverde. If we are to adequately define the controls on the spatial distribution of both oil and gas in the Mesaverde, it is essential to understand the relative time of gas generation (single or multiple events), time of formation of cements relative to time of oil and gas generation, and time of water incursion in the updip section relative to gas generation. Simply looking at the present configuration without understanding the sequence of events that define the configuration may lead to false assumptions. Research that should be undertaken would include isotopic age-dating of produced water using both ^{36}Cl or ^{129}I and obtaining isotopes on the cements in the order in which they formed.

SUMMARY

The new, detailed studies of the Mesaverde presented in this report give us a better understanding of the lateral variability in depositional environments and facies. Recognition of this lateral variability and establishment of the criteria for separating deltaic, strandplain-barrier, and estuarine deposits from each other permit development of better hydrocarbon exploration models, because the sandstone geometry differs in each depositional system. Although these insights will provide better exploration models for gas exploration, it does not appear that they will be instrumental in finding more oil, except as a by-product of gas production in the Blanco field. The lack of current and past conventional oil production in the Mesaverde is an enigma. Oil is produced from isolated fields; only a few wells define each field. Production is from sandstone beds in the upper part of the Point Lookout Sandstone or from individual fluvial channel sandstones in the Menefee. Source of the oil in the Menefee and Point Lookout may be from interbedded organic-rich mudstones or coals rather than from the Lewis Shale. The Lewis Shale appears to contain more type III organic matter and, hence, should produce mainly gas. Outcrop studies have not documented oil staining that might point to past oil migration through the sandstones of the Mesaverde. The lack of oil production may be related to the following: 1) lack of abundant organic matter of the type I or II variety in the Lewis Shale needed to produce oil, 2) ineffective migration pathways due to discontinuities in sandstone reservoir geometries, 3) cementation or early formation of gas prior to oil generation that reduced effective permeabilities and served as barriers to updip migration of oil, or 4) erosion of oil-bearing reservoirs from the southern part of the basin.

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